Future Opportunities
at an
Electron-Ion Collider

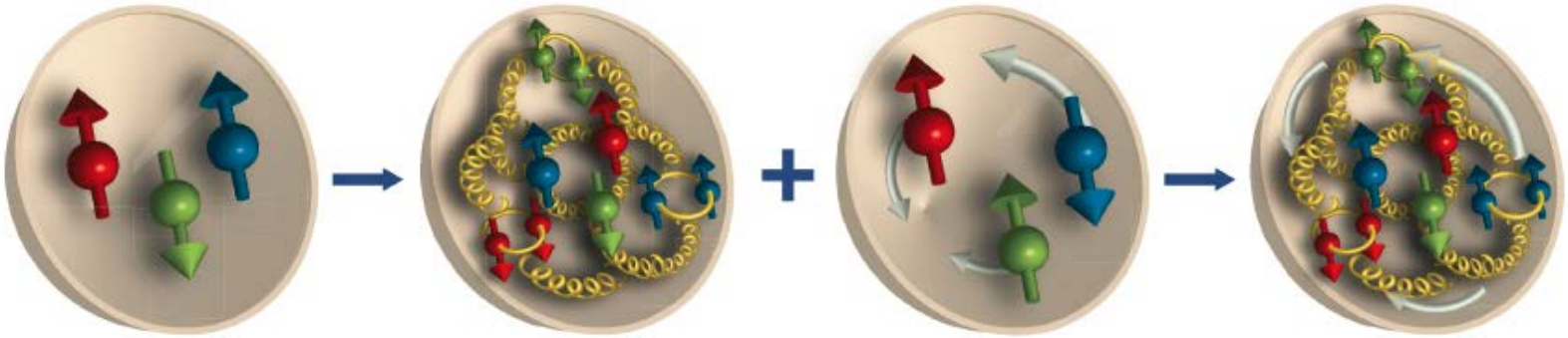
K. Oleg Eyser

BROOKHAVEN
NATIONAL LABORATORY

Exploring the Glue that Binds Us All

- Questions at the next QCD frontier
  - How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
  - Where does the saturation of gluon densities set in?
  - How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?
- An Electron-Ion Collider
  - Electron beams for precision measurements
  - Polarized nucleon beams
  - Heavy ion beams of different species
  - Kinematic reach into the gluon dominated regime
  - Dedicated hermetic detector setup

The Structure of the Nucleon



- What is the dynamical origin of sea quarks and gluons inside the proton?
- How does the proton spin originate at the microscopic level?
- How is hadron structure influenced by chiral symmetry and its breaking?
- How does confinement manifest itself in the structure of hadrons?

Partonic Descriptions of the Nucleon

$W(x,b_T,k_T)$
Wigner distributions

$\int d^2b_T$ $\int d^2k_T$

Fourier trf.
$b_T \leftrightarrow \Delta$

$\xi = 0$

$f(x,k_T)$ $f(x,b_T)$ $H(x,0,t)$ $t=-\Delta^2$ $H(x,\xi,t)$

transverse momentum distributions (TMDs)
semi−inclusive processes

impact parameter distributions

generalized parton distributions (GPDs)
exclusive processes

$\int d^2k_T$ $\int d^2b_T$ $\int dx$ $\int dx x^{n-1}$

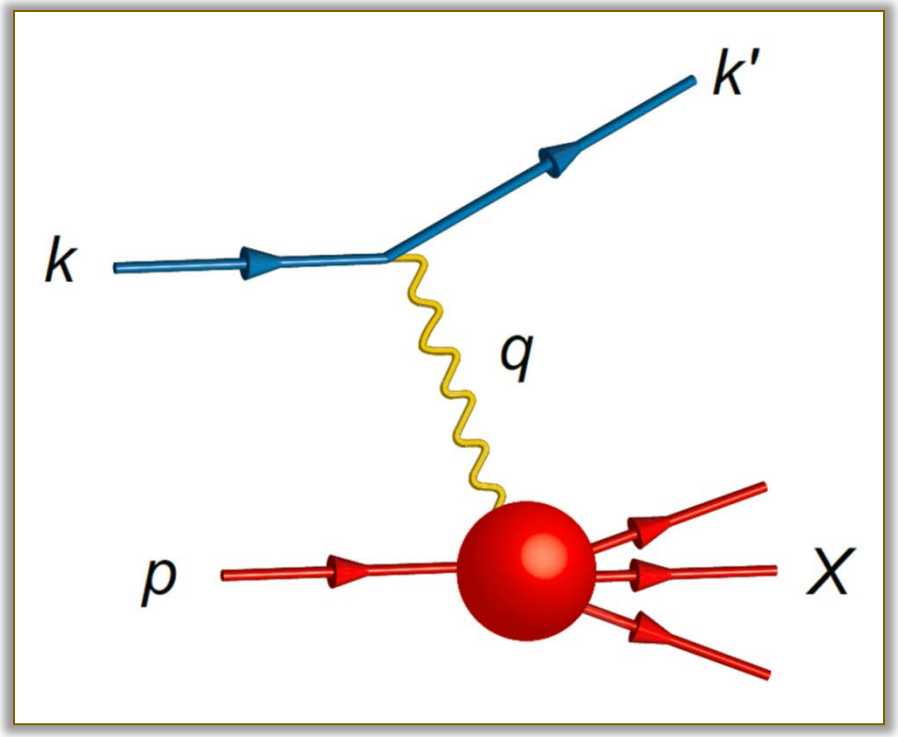
$f(x)$ $F_1(t)$ $A_{n,0}(t)+4\xi^2 A_{n,2}(t)+....$

parton densities
inclusive and semi−inclusive processes

form factors
elastic scattering

generalized form factors
lattice calculations

Deep Inelastic Scattering



Lorentz invariants

$$s = (p + k)^2 = 4 \cdot E_p \cdot E_e$$

$$Q^2 = -q^2 = -(k - k')^2$$

$$x_B = \frac{Q^2}{2 \cdot p \cdot q}$$

$$y = \frac{q \cdot p}{k \cdot p}$$

$$Q^2 = x \cdot y \cdot s$$

Other variables $W^2 = (p + q)^2 = Q^2 \cdot (1 - 1/x)$

$$\nu = \frac{q \cdot p}{M} = \frac{y \cdot s}{2M}$$

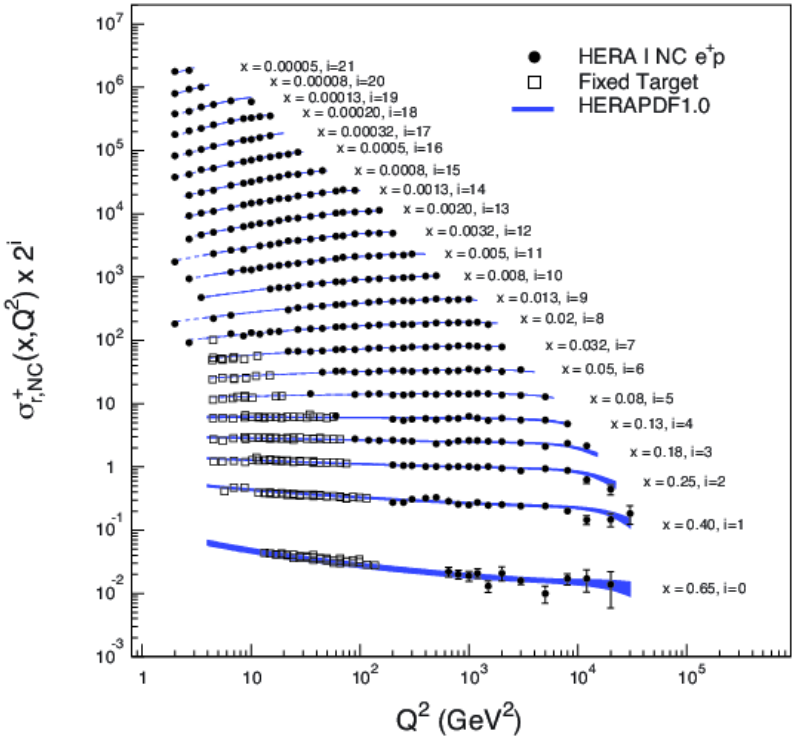
In the collider frame

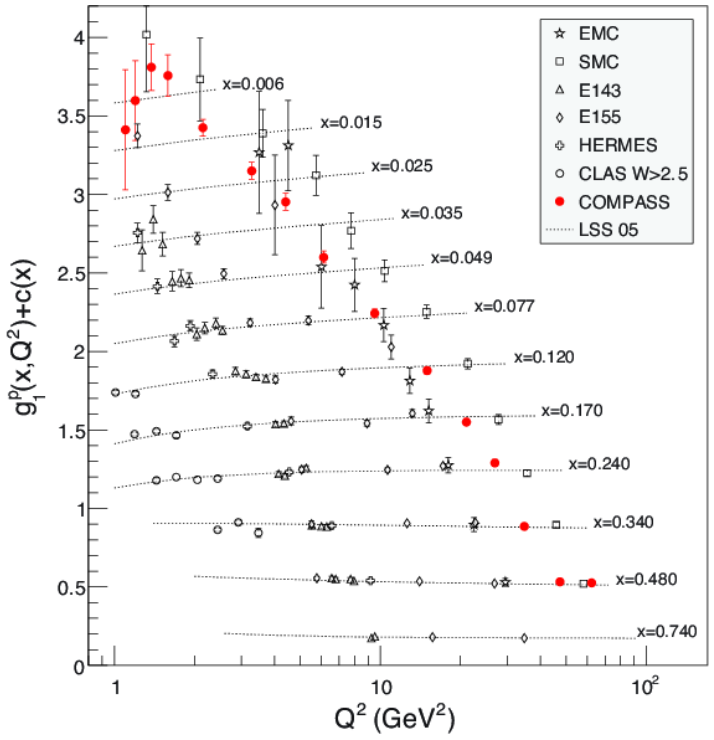
$$E'_e = E_e \cdot (1 - y) + \frac{Q^2}{4 \cdot E_e}$$

Structure Functions

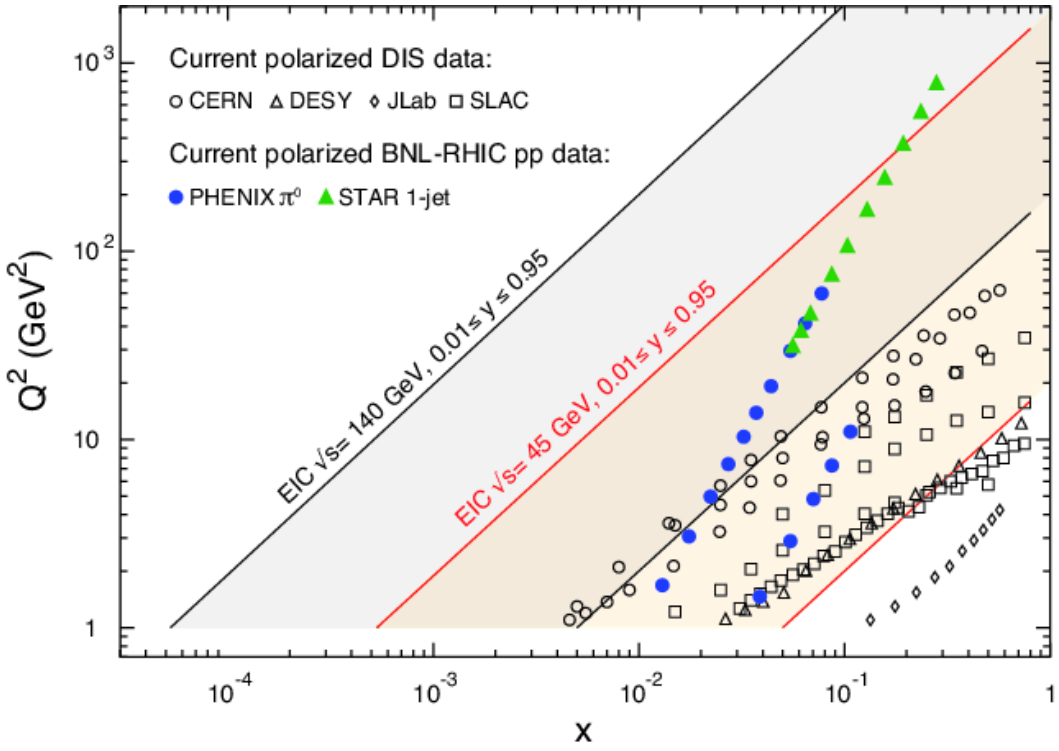
$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right] \qquad \sigma_r = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

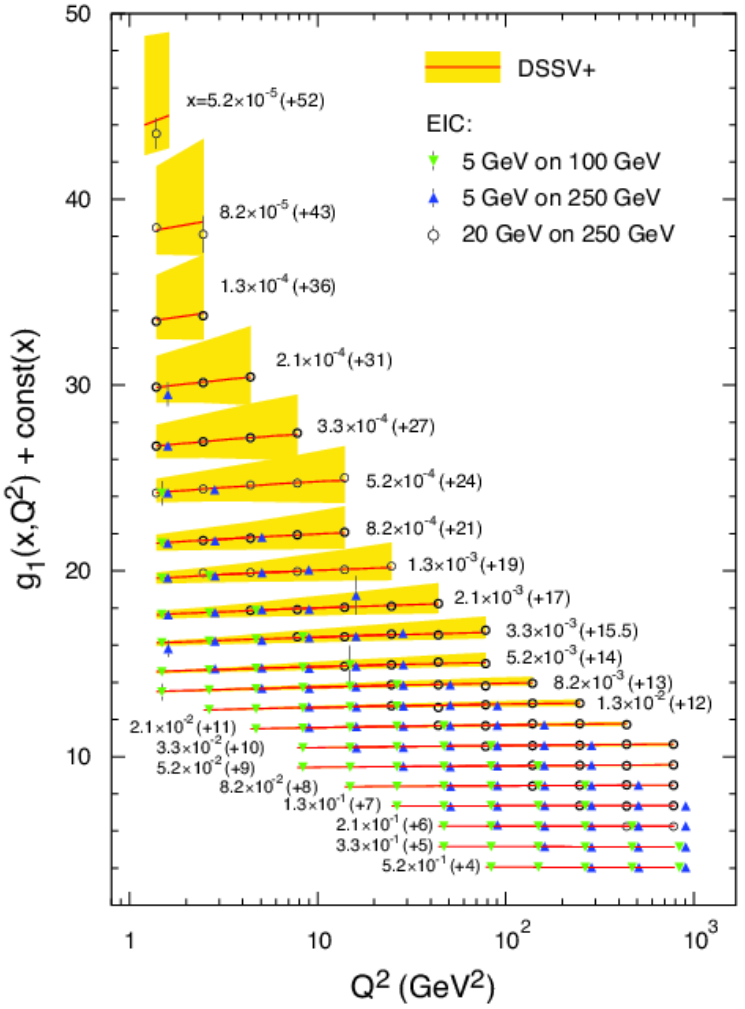
$$F_2(x,Q^2) = x\sum e_q^2[q(x,Q^2) + \bar{q}(x,Q^2)] \qquad g_1(x,Q^2) = x\sum e_q^2[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)]$$





Longitudinal Spin Structure



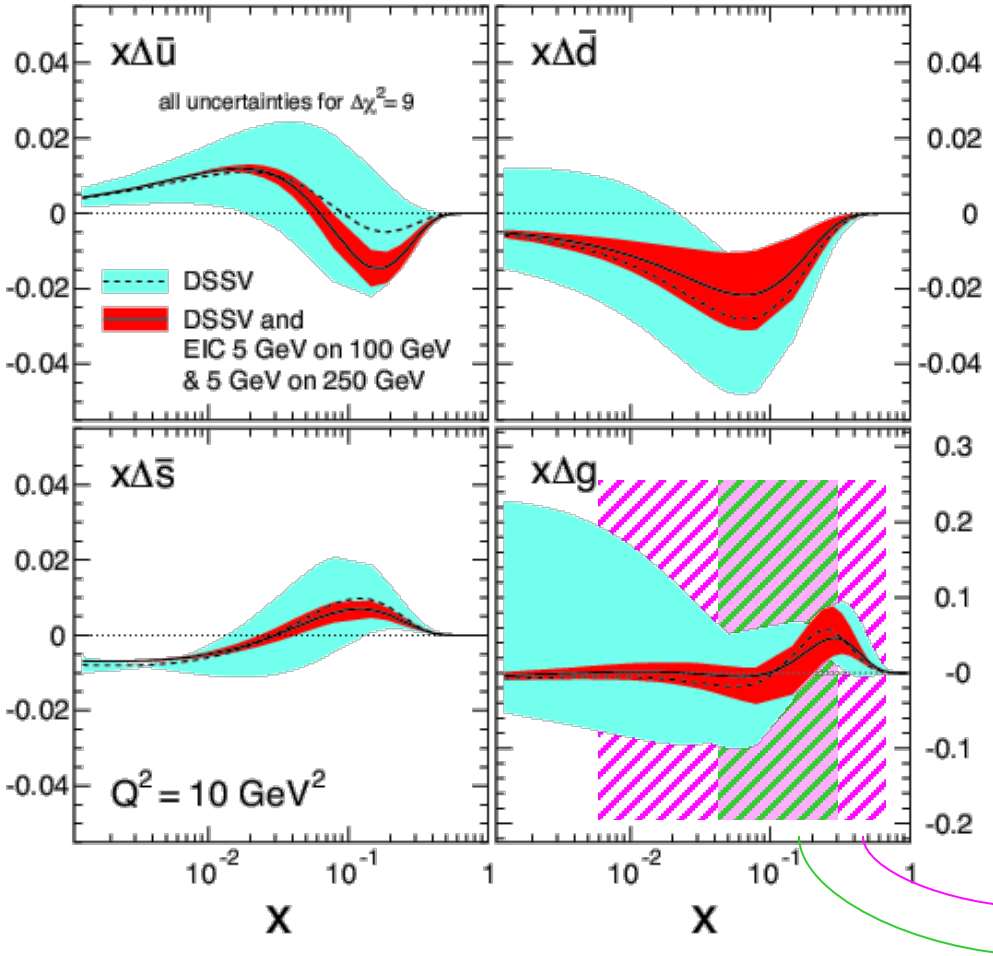


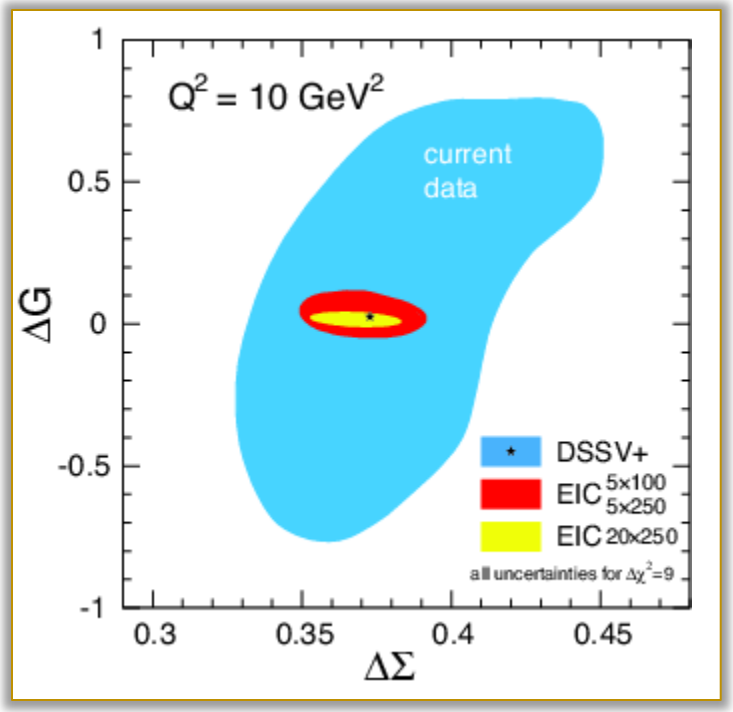
EIC pseudo data based on PEPSI Monte-Carlo

$L_{int} = 10\ \mathrm{fb}^{-1}$

$Q^2_{min} = 1\ \mathrm{GeV}^2,\ W^2 > 10\ \mathrm{GeV}^2,\ 0.01 < y < 0.95$

Longitudinal Spin Structure

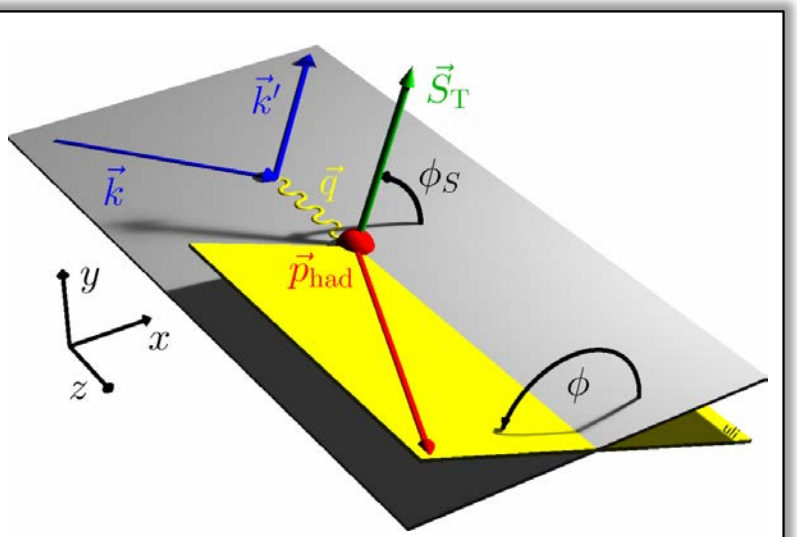




current *e+p*

current *p+p*

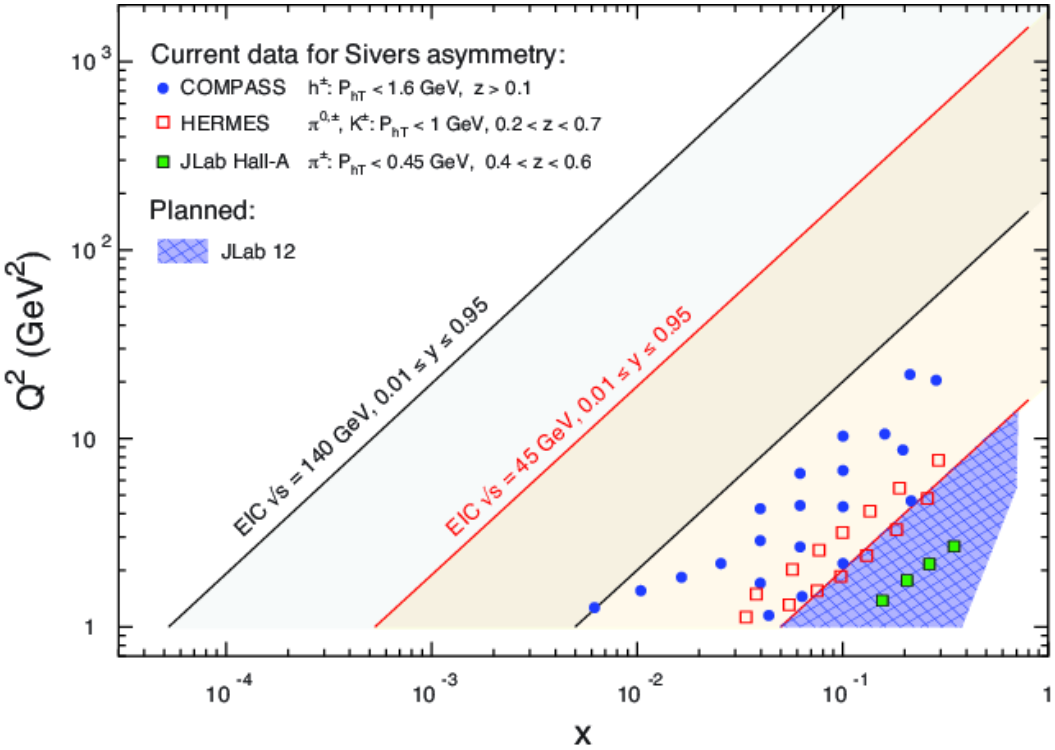
Quark TMD Distributions in SIDIS



Transverse momentum p_T

Fragmentation $z = \frac{P_h \cdot P}{q \cdot P}$

Azimuthal correlation φ, φ_S



Quark TMD Distributions

$$\frac{d\sigma}{dxdyd\varphi dzd\varphi_S dp_T^2} \propto F_{UU,T} + |S_\perp| \sin(\varphi - \varphi_S) F_{UT,T}^{\sin(\varphi-\varphi_S)} + \cdots$$

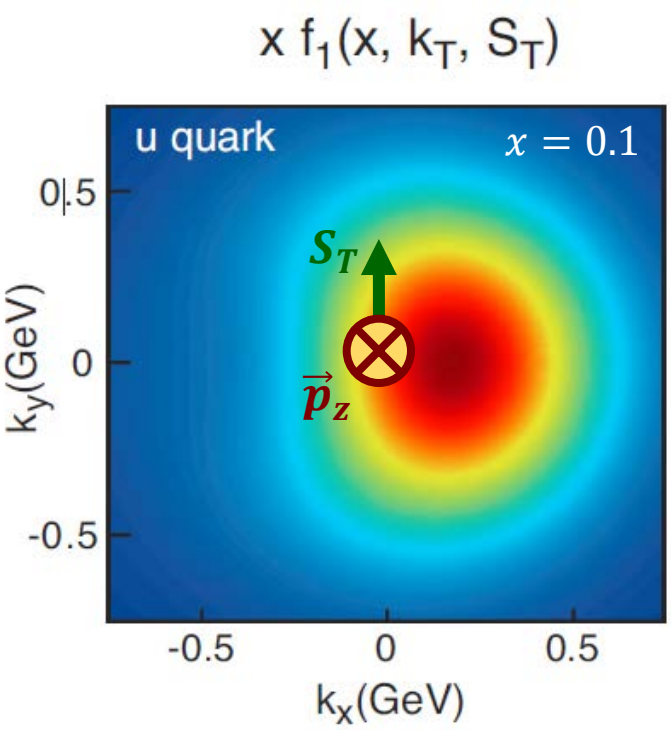
$$\Downarrow$$

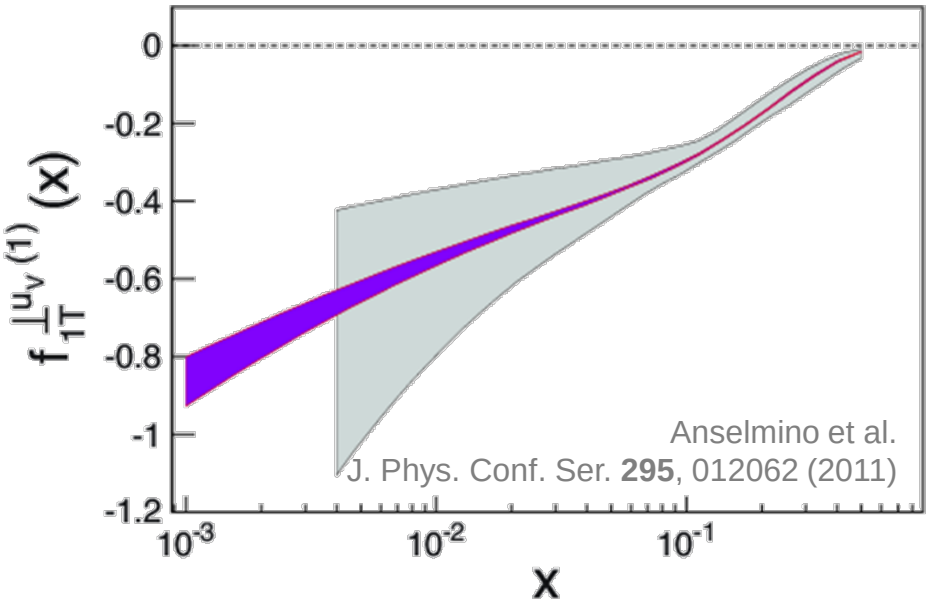
$$f_{1T}^{\perp q}(x, k_T)$$

EIC pseudo data

$\sqrt{s} = 45$ GeV

$L_{int} = 10$ fb^{-1}



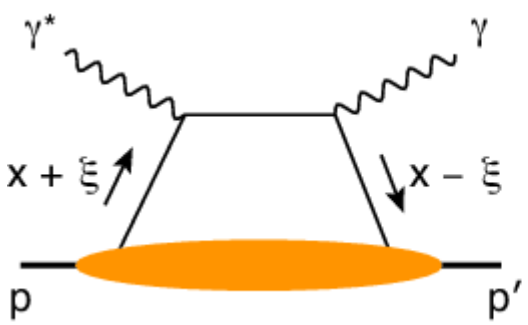


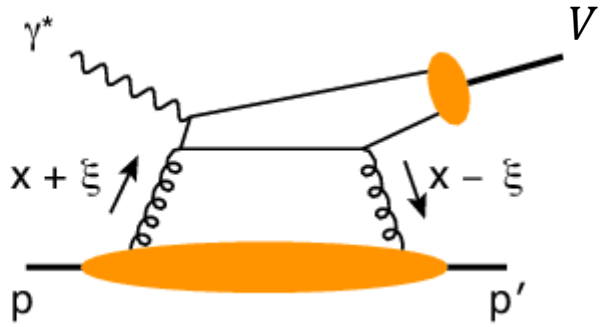
Spatial Imaging of Nucleons

$$f^{\Uparrow}(x, b_T) = f(x, b_T^2) + \frac{(S_T \times b_T)^z}{M} \frac{\partial}{\partial b_T^2} e(x, b_T^2)$$

$f(x, b_T^2)$, $e(x, b_T^2)$ } Fourier transform of { $H(x, \xi, t)$, $E(x, \xi, t)$ } at $\xi = 0$

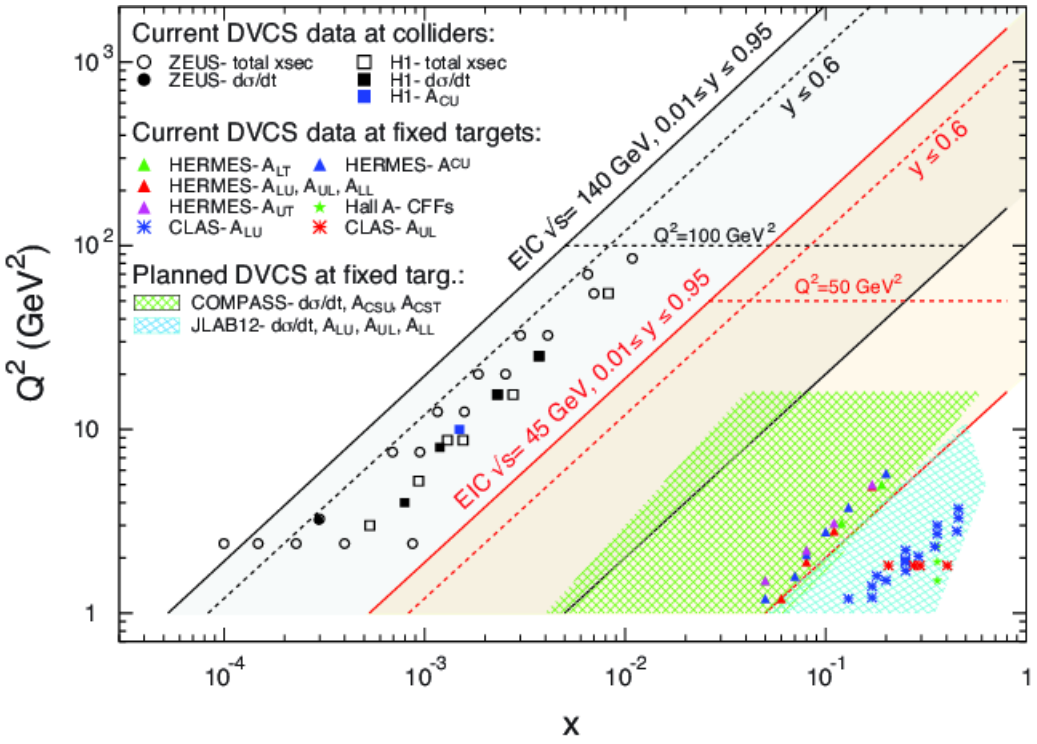
Exclusive processes to measure generalized parton distribution functions:

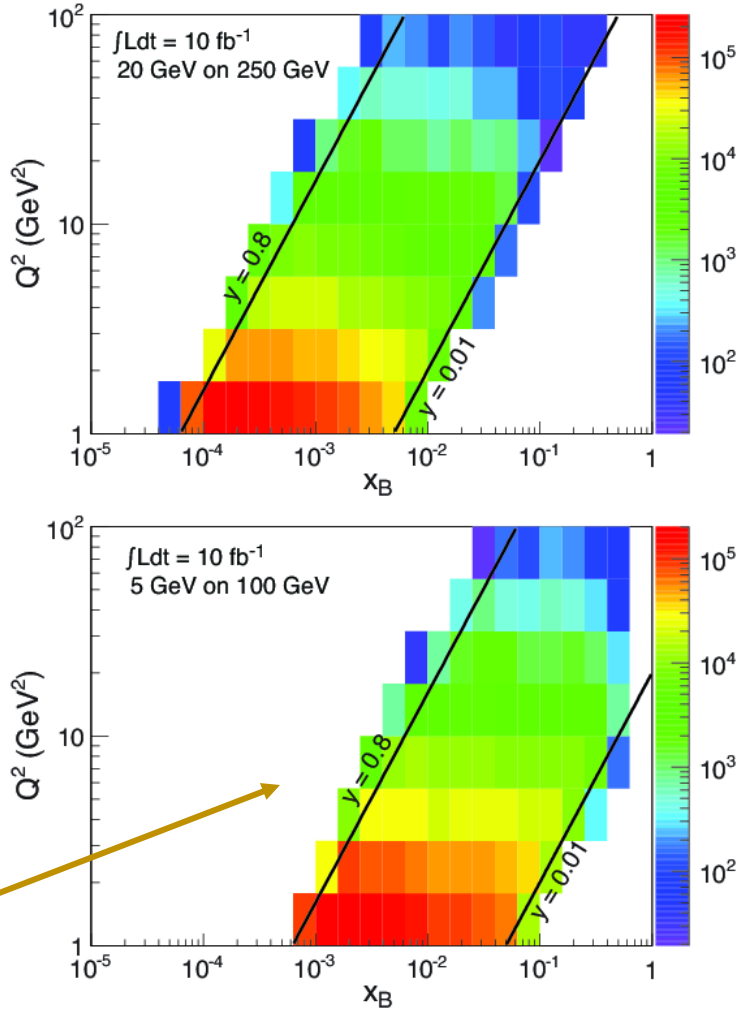




Resolution scale Q^2 $M_V^2 + Q^2$

Deeply Virtual Compton Scattering



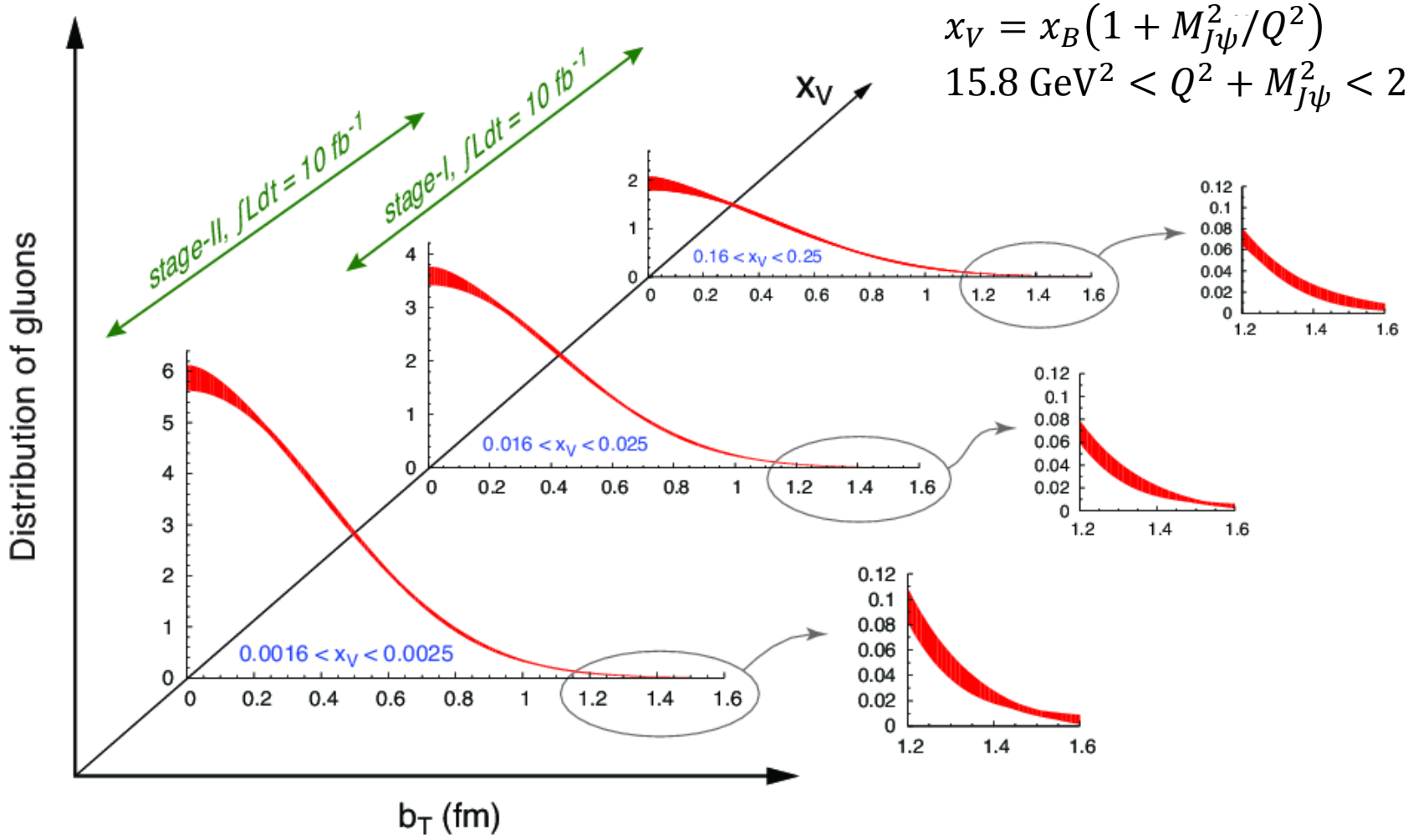


For spatial imaging measure $\frac{d\sigma}{dt}$

Need binning in x_B and Q^2

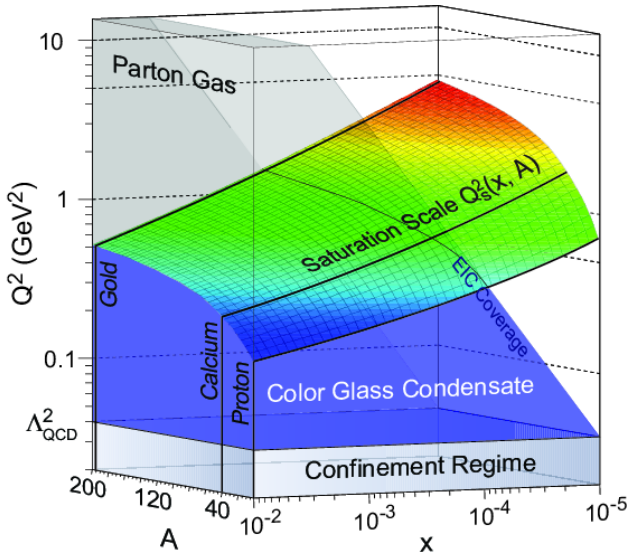
Gluon Distributions

$$x_V = x_B\left(1 + M_{J\psi}^2/Q^2\right)$$
$$15.8\ \mathrm{GeV}^2 < Q^2 + M_{J\psi}^2 < 25.1\mathrm{GeV}^2$$

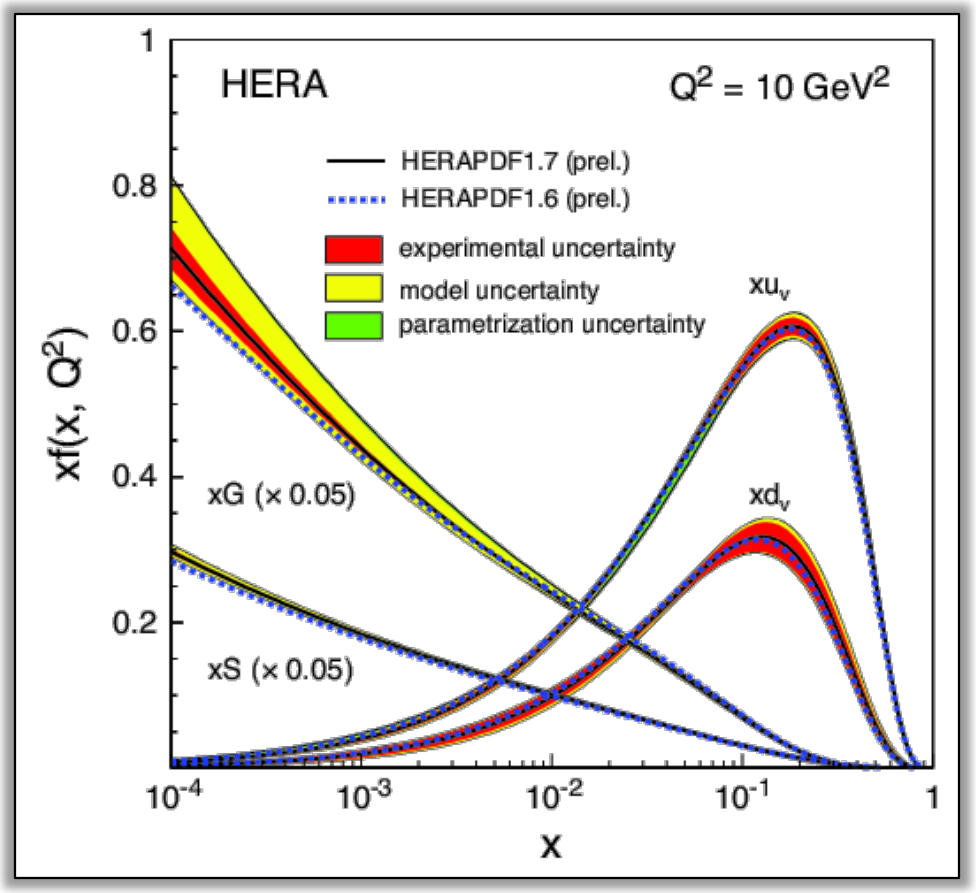


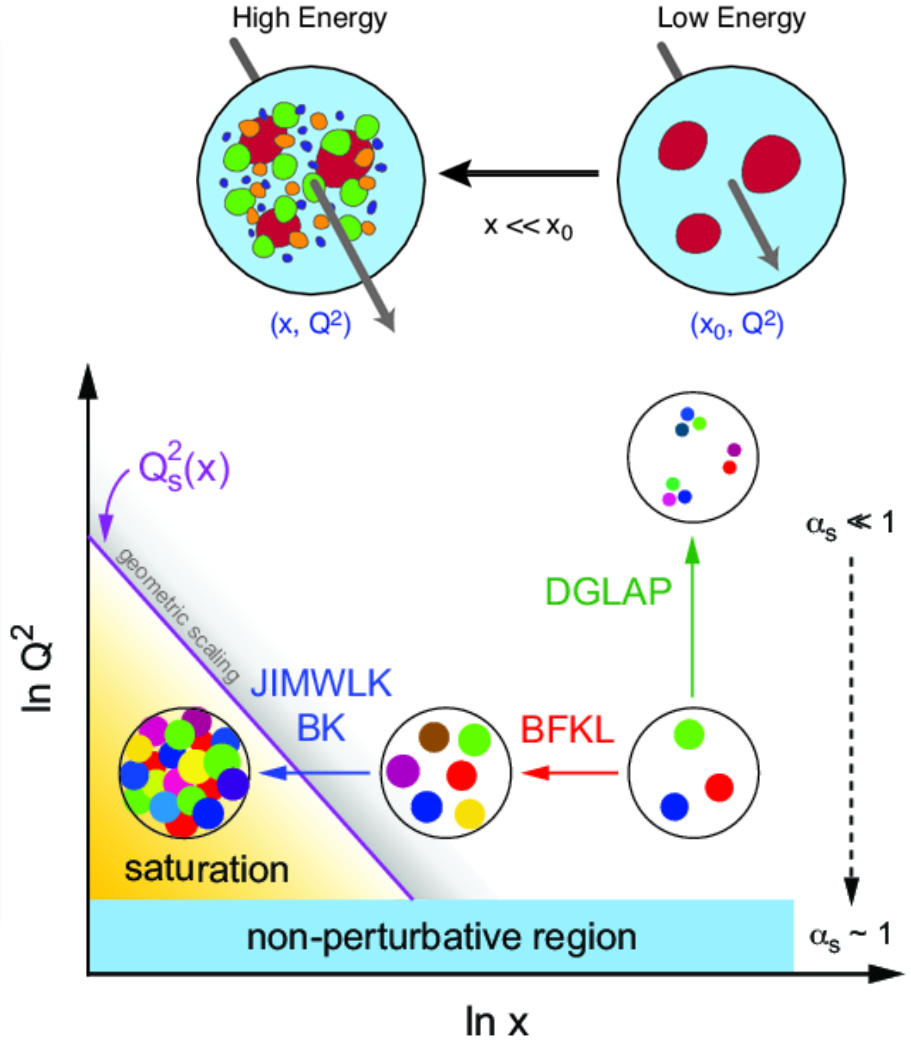
The Nucleus: A Laboratory for QCD

- What is the role of strong gluon fields, parton saturation effects, and collective gluon excitations in nuclei?
- Can we experimentally find evidence of non-linear QCD dynamics in the high-energy scattering off nuclei?
- What are the momentum/spatial distributions of gluons and sea quarks in nuclei?
- Are there strong color fluctuations inside a large nucleus?

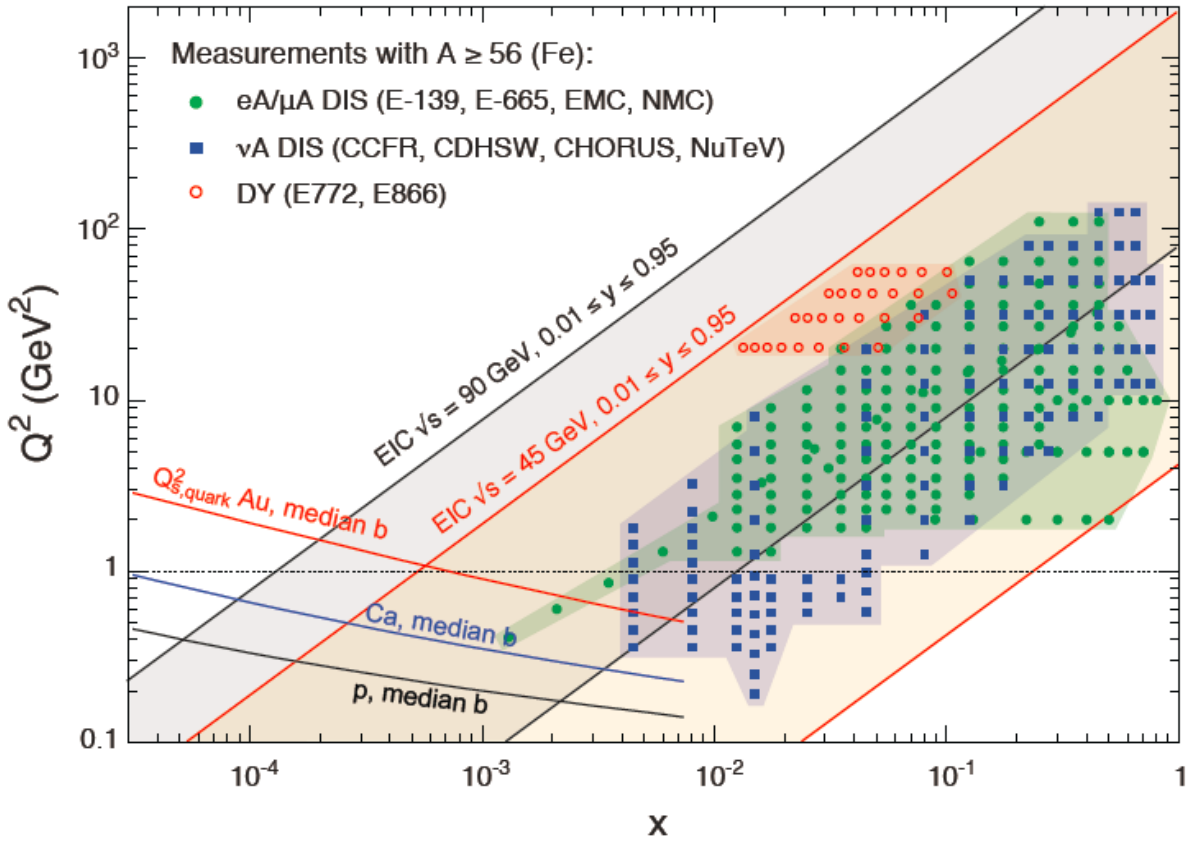


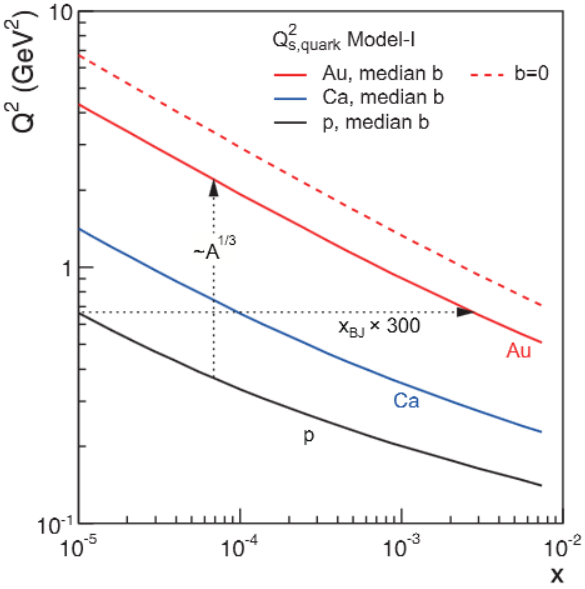
High Gluon Densities in Nuclei





Lepton-Nucleus Scattering





u.r. boost amplifies the gluon densities in nucleus ($R \sim A^{1/3}$)

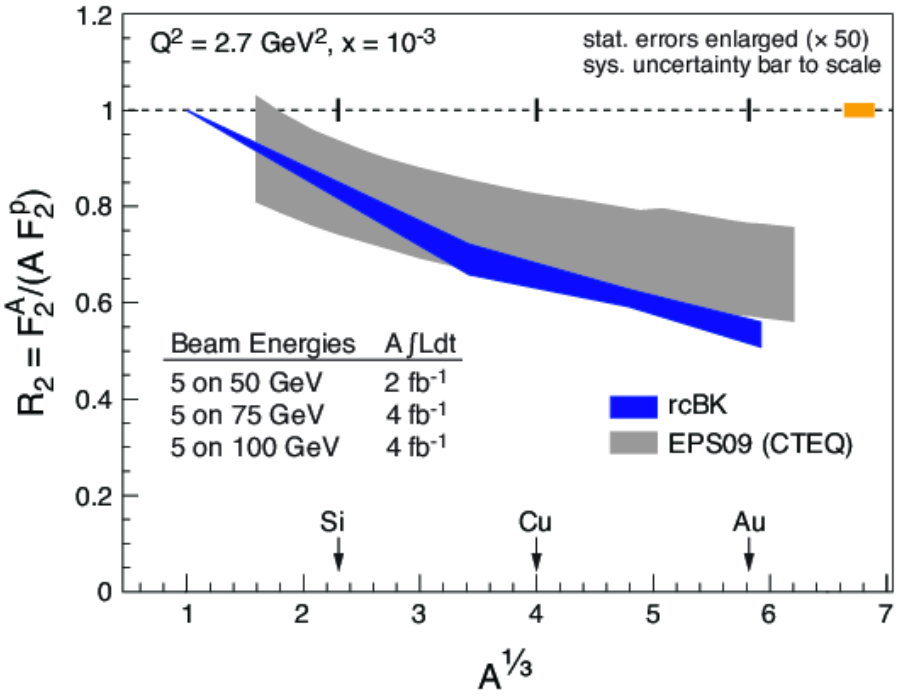
$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

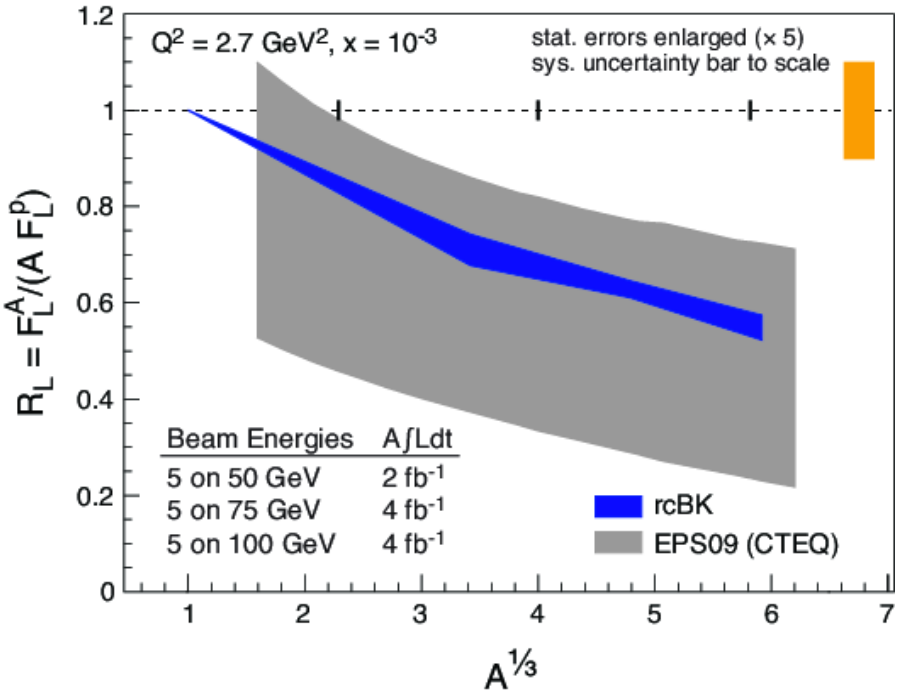
Nuclear PDFs

Expect strong non-linear effects in F_L from higher twist contributions

Dipole model from Bartels et al.

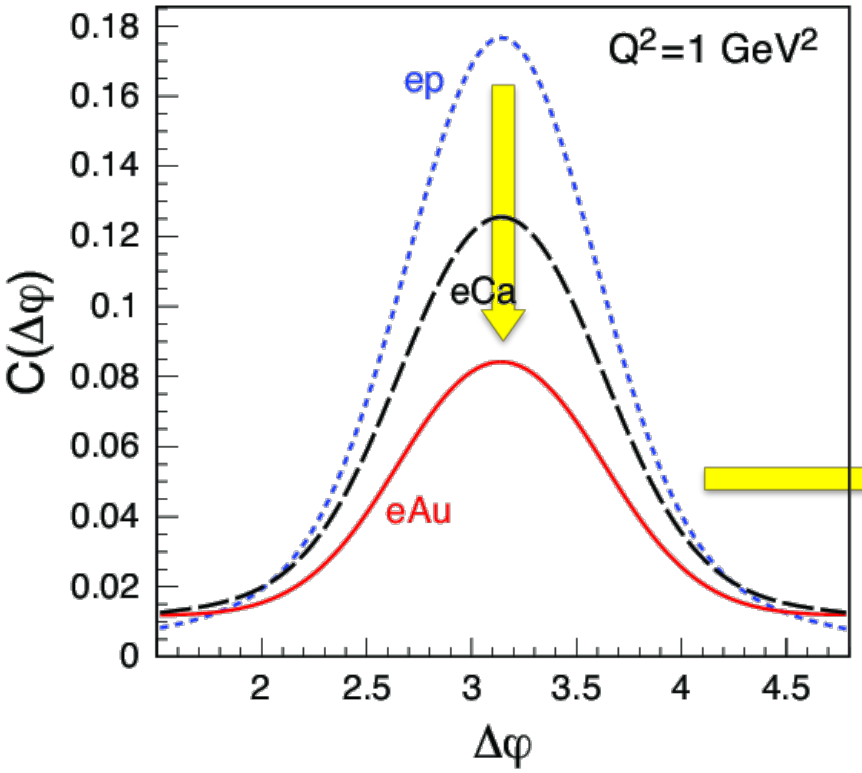
Quantify by $R_{2/L}(x,Q^2) = \frac{F^A_{2/L}(x,Q^2)}{A \cdot F^p_{2/L}(x,Q^2)}$





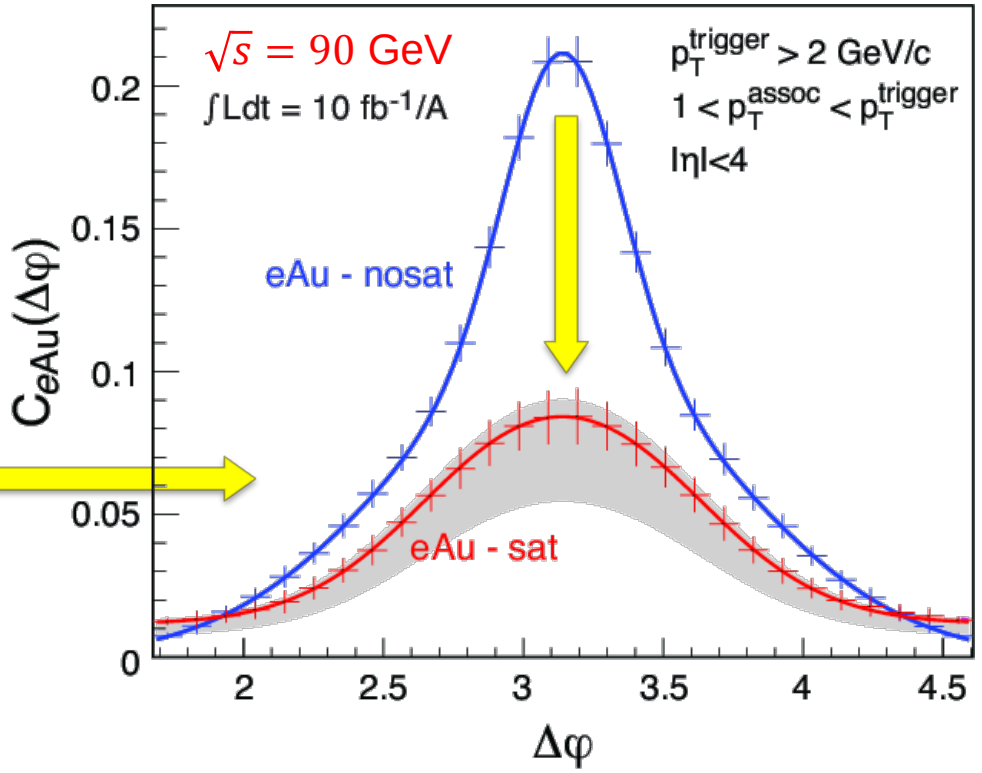
Di-hadron Correlations

Prediction in CGC framework



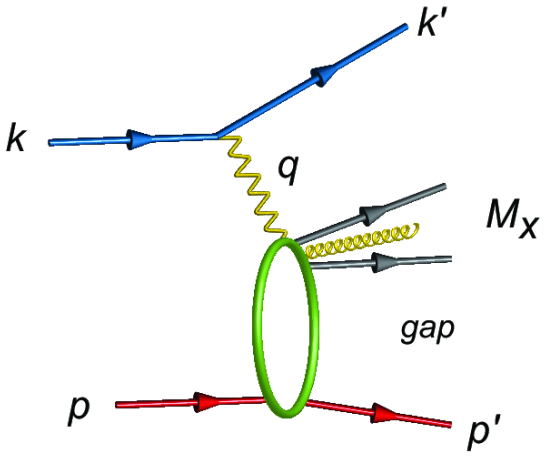
PRD 83, 1 5005 (2011)
PRL 106, 022301 (2011)

Expected experimental significance



with EPS09 (nPDF shadowing)
PYTHIA6 (partons, showers, fragmentation)
DPMJet-III (nuclear geometry)

Diffractive Scattering



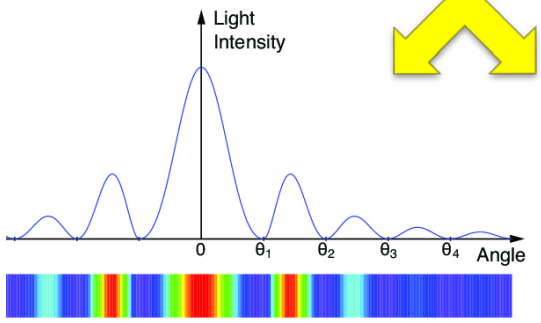
$$t = (p - p')^2$$

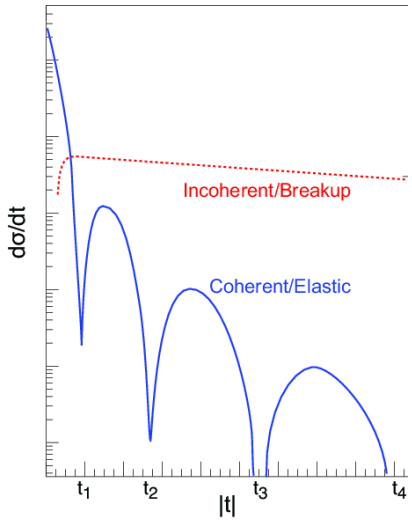
$$M_X^2 = (p - p' + k - k')^2$$

Rapidity gap

$$\eta = -\frac{1}{2}\ln\left(\tan\theta/_2\right)$$

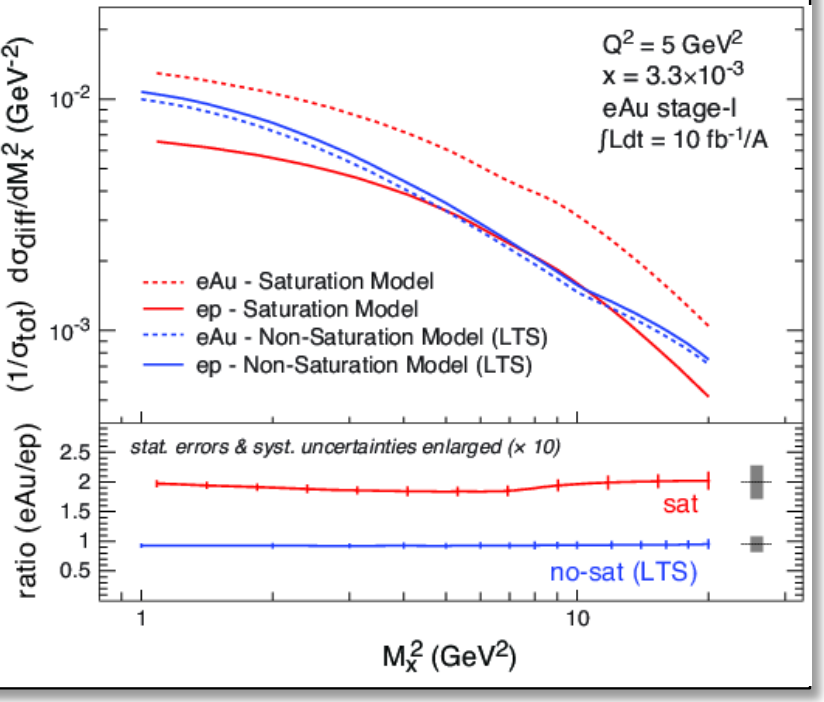
$$|t| \approx k^2\theta^2$$





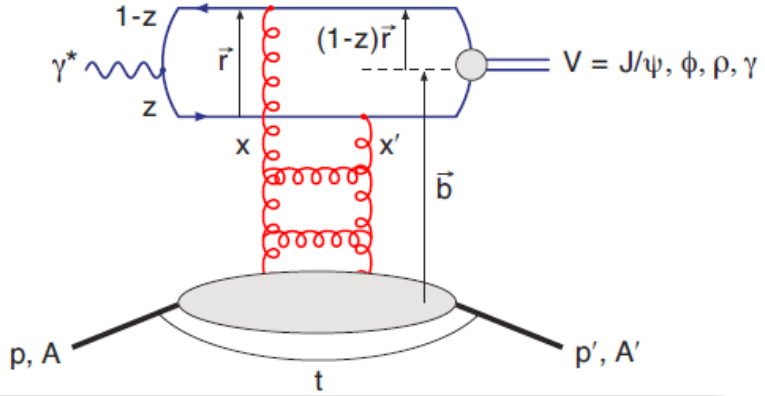
Black disc limit $\frac{\sigma_{diff}}{\sigma_{tot}} = 0.5$

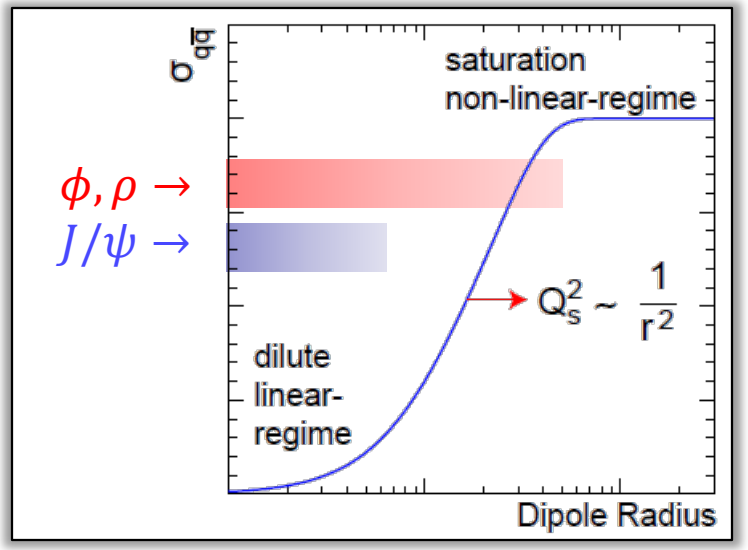
Non-linear effects amplify σ_{diff} in e+A

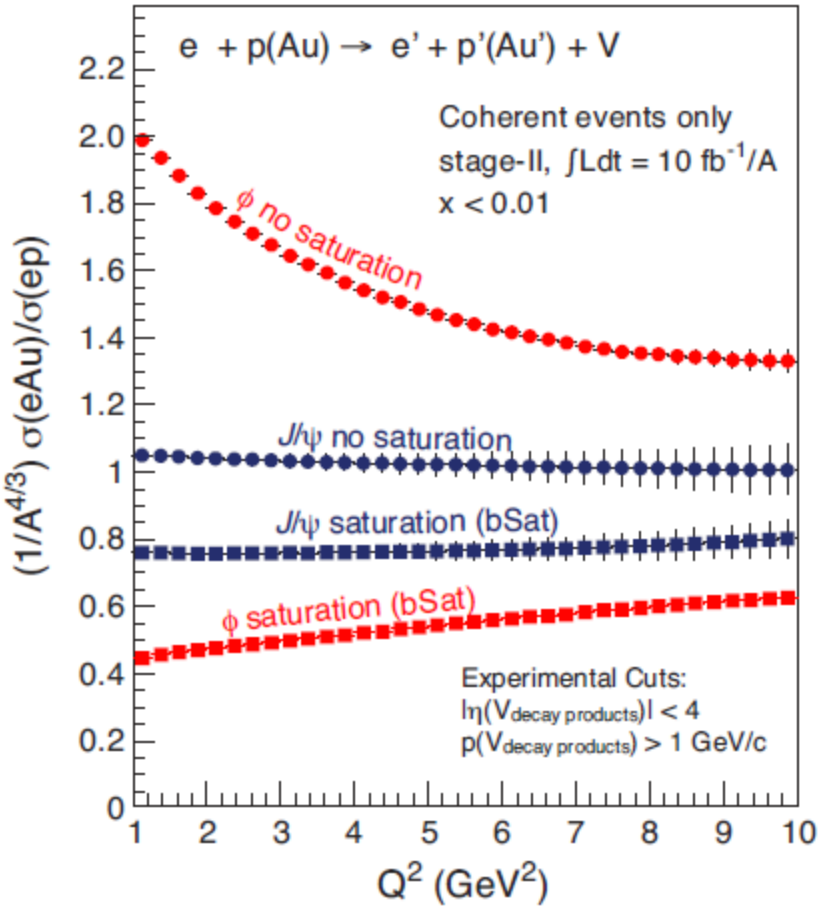


Exclusive Vector Meson Production

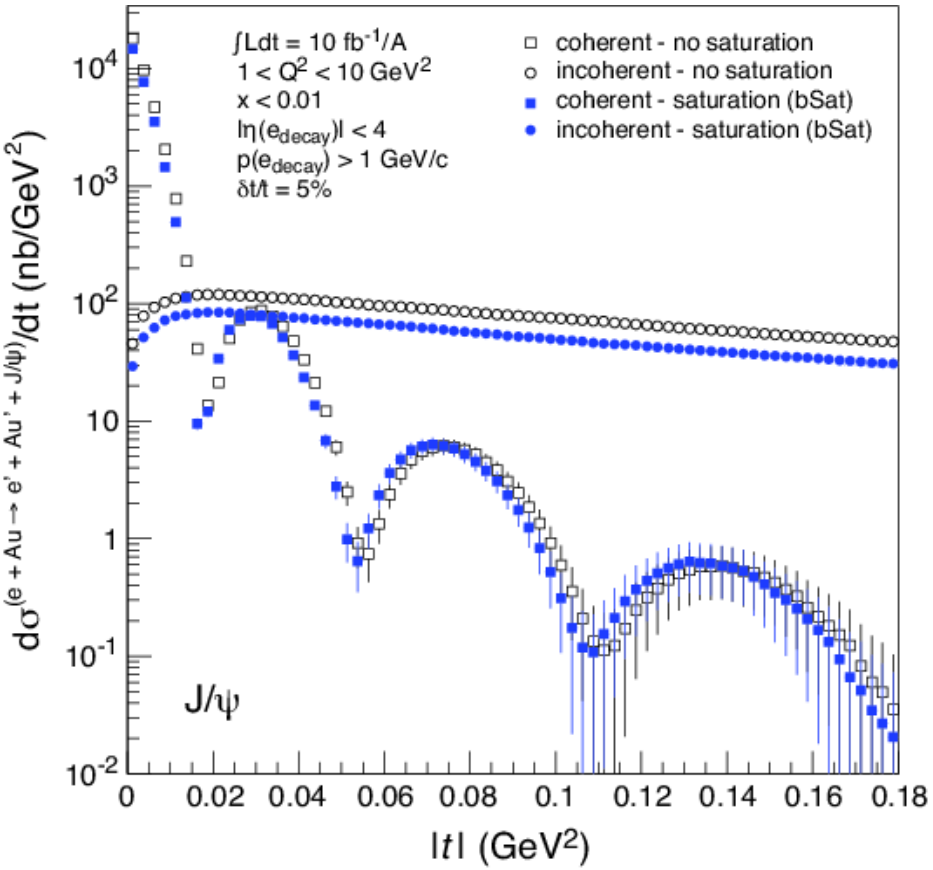
Fix momentum transfer $t = (p_A - p_{A'})^2 = (p_{VM} + p_{e'} - p_e)^2$

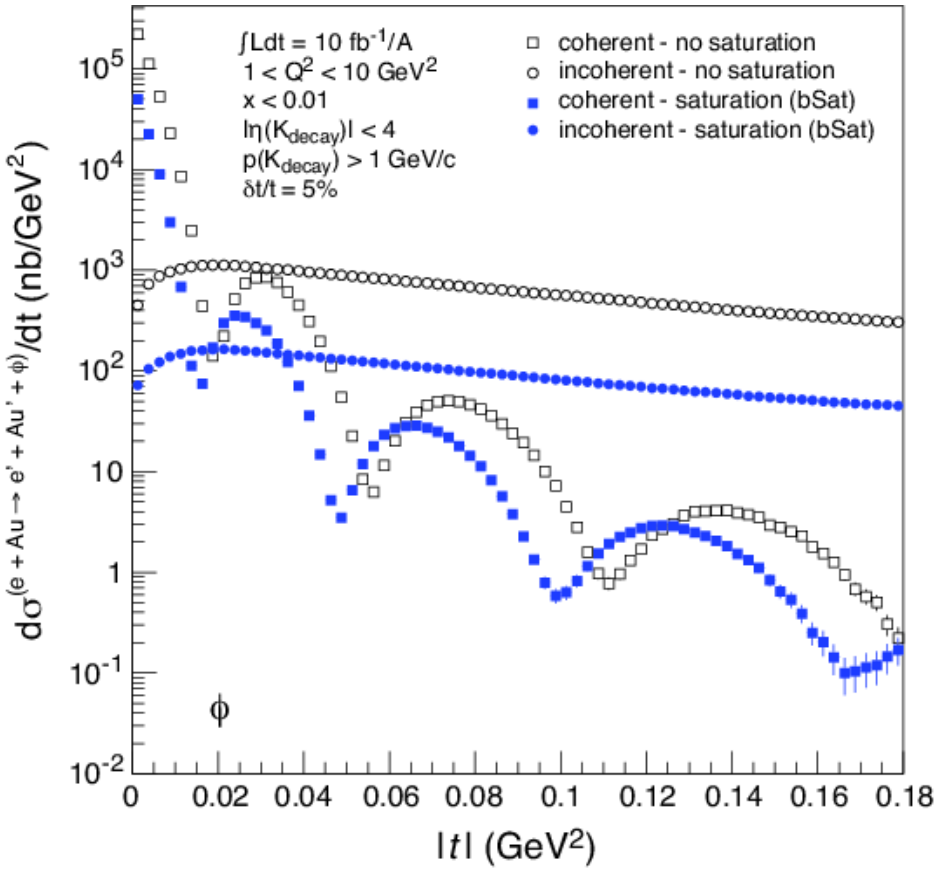




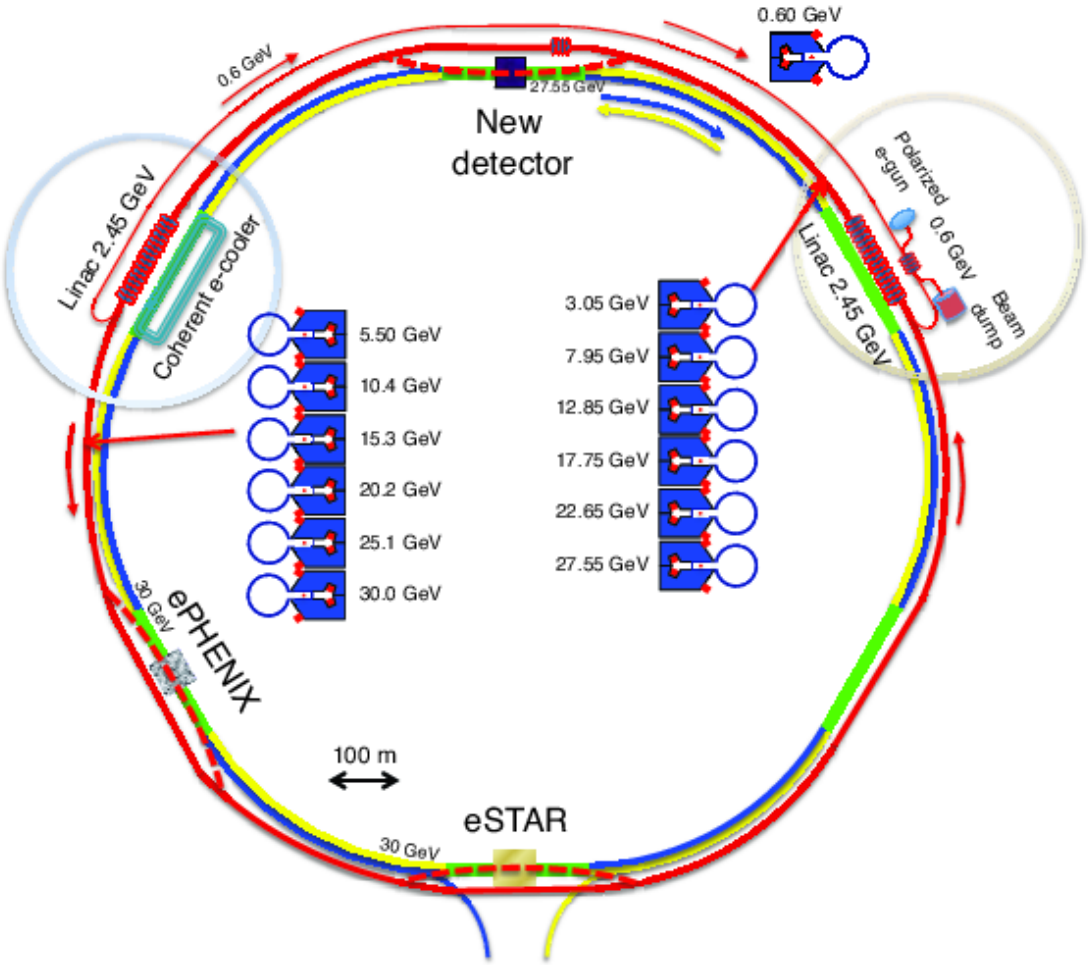


Spatial Gluon Distribution

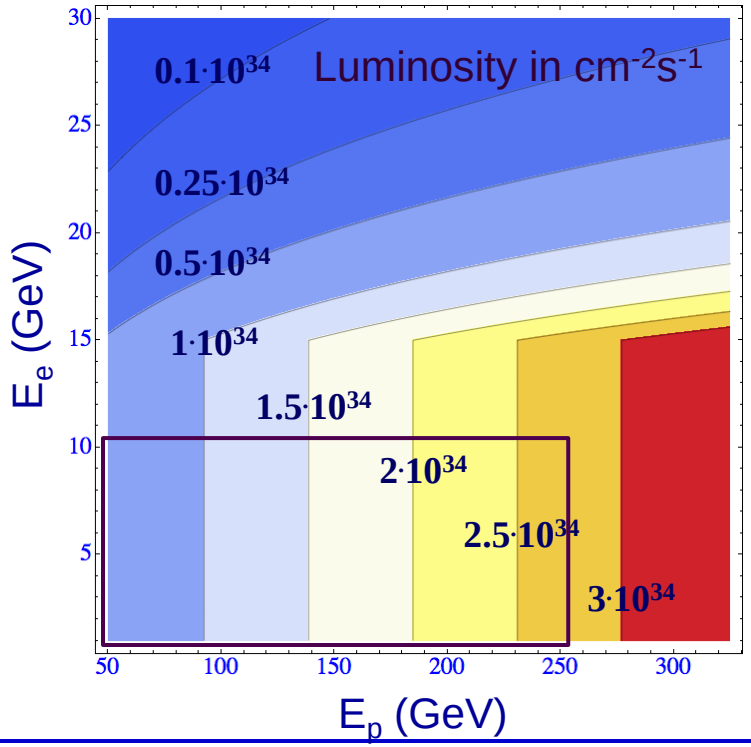




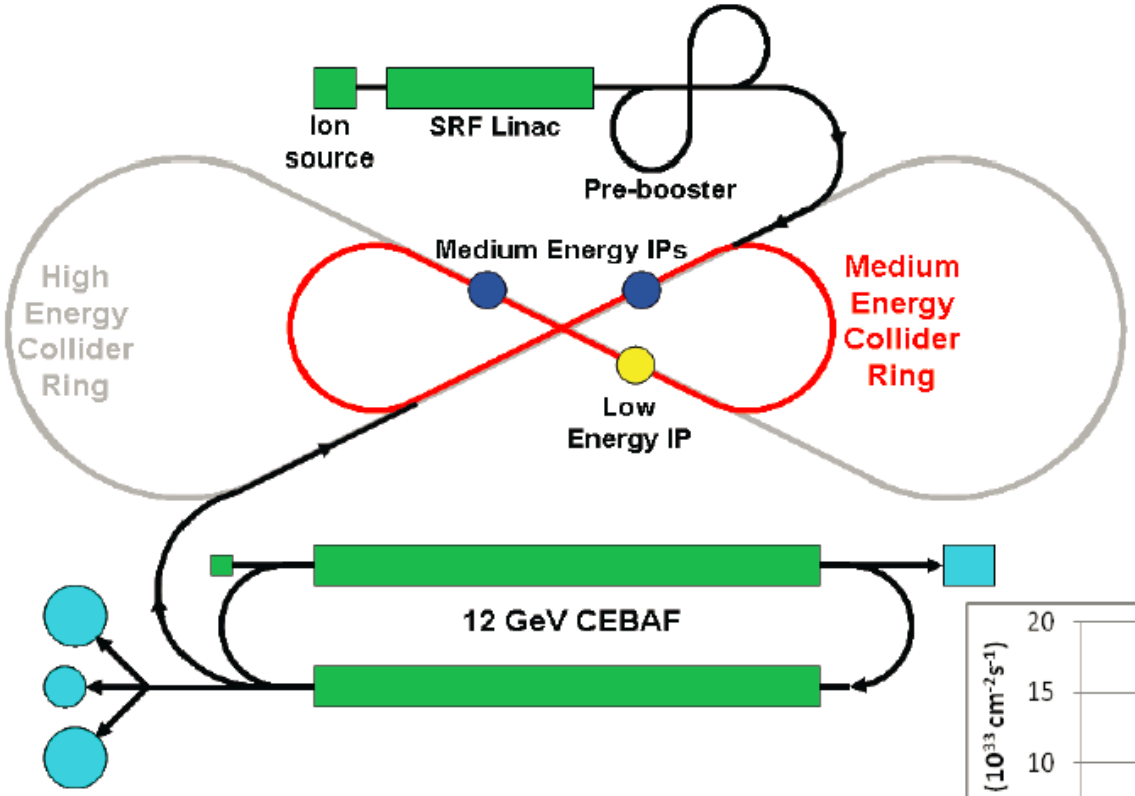
ERL eRHIC



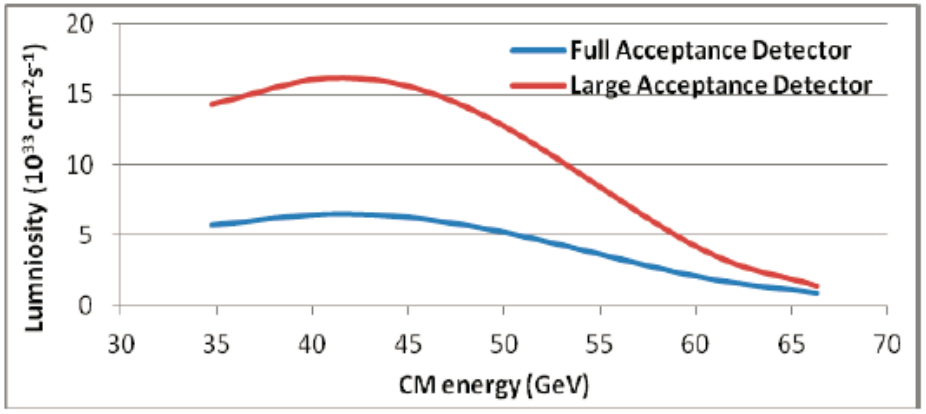
Electron beam energy	10 GeV
Proton beam energy	250 GeV
Ion beam energy	100 GeV/u
Electron beam polarization	80%
Proton beam polarization	70%



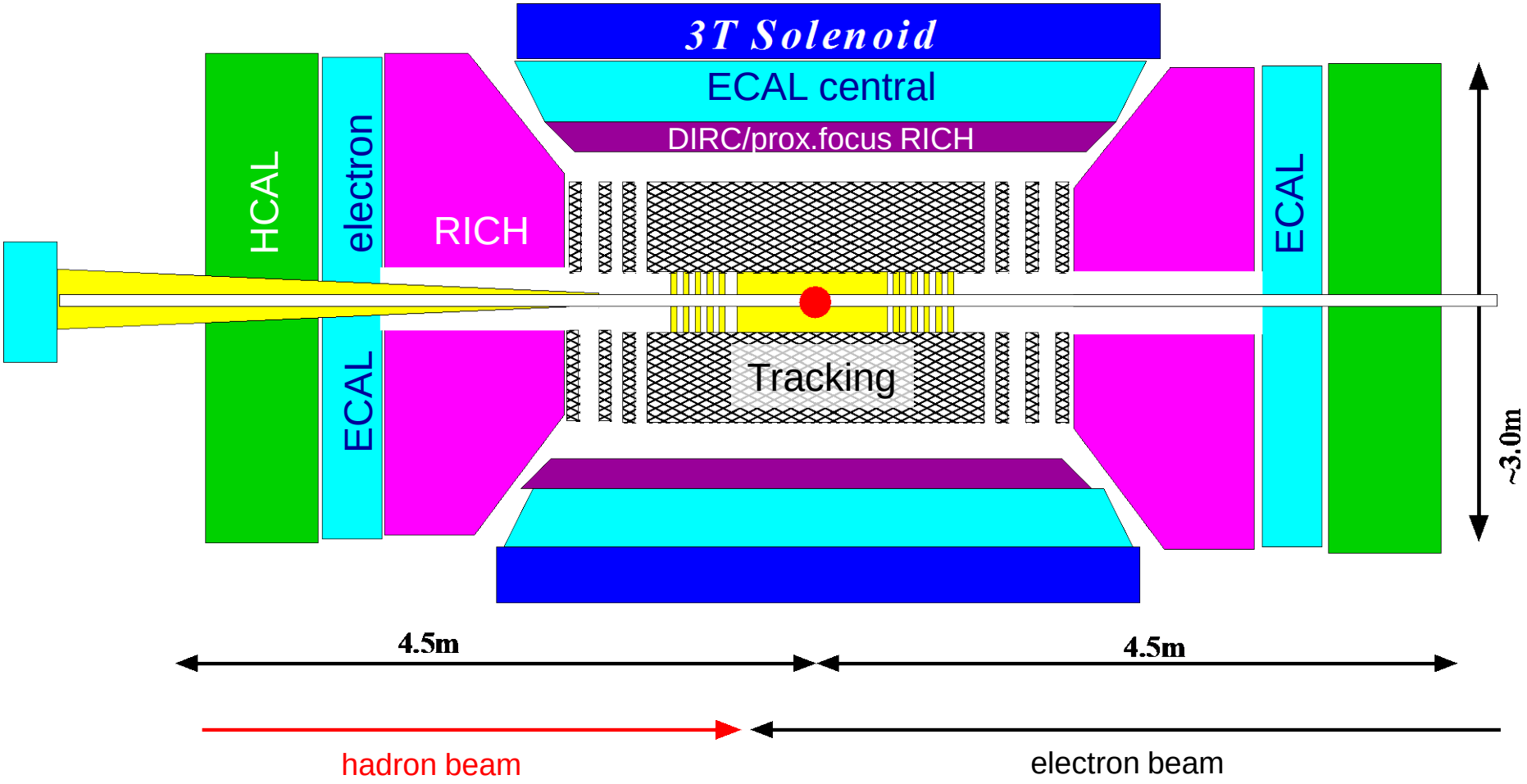
mEIC/ELIC

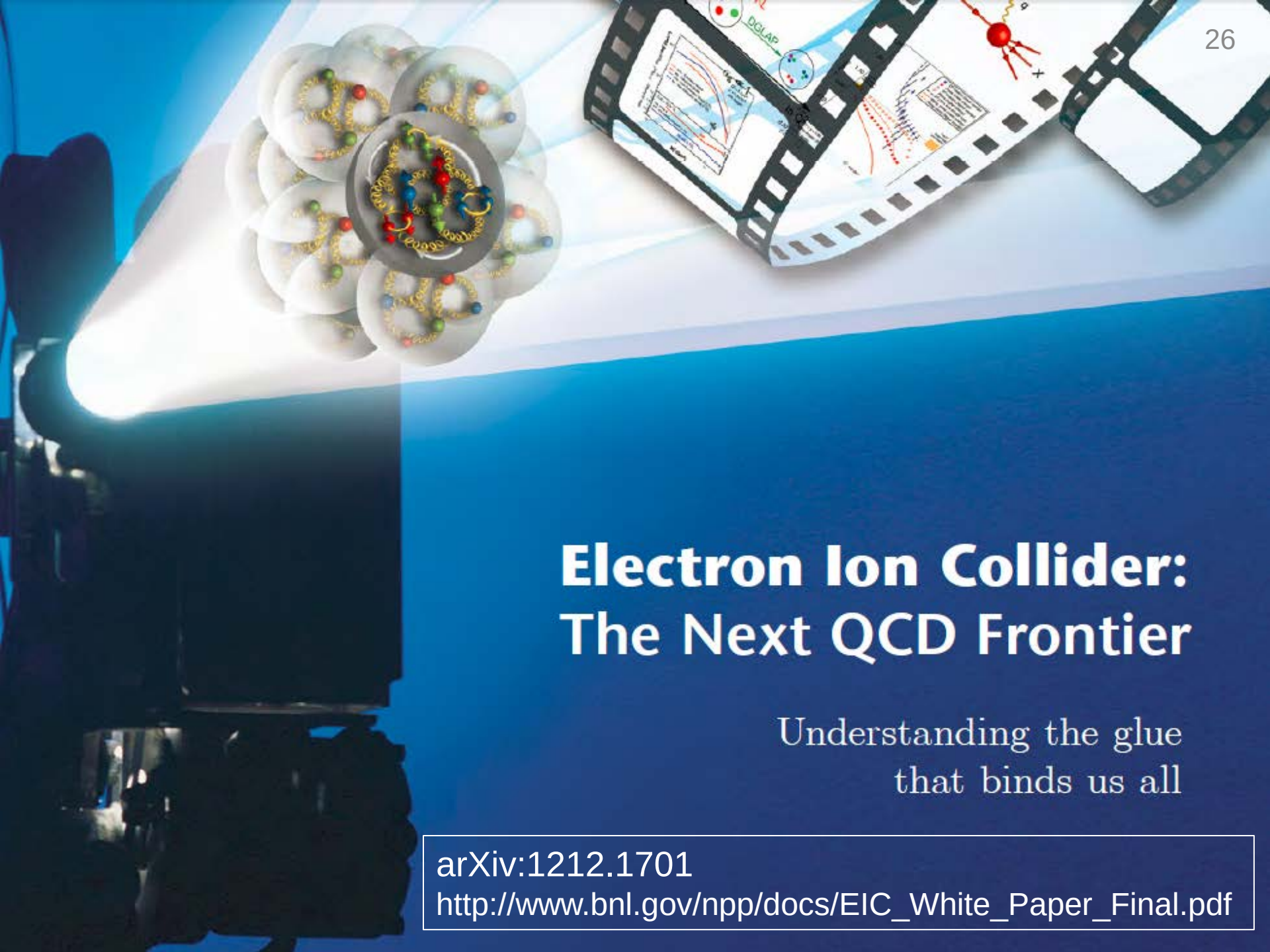


Electron beam energy	5 GeV
Proton beam energy	100 GeV
Ion beam energy	40 GeV/u
Electron beam polarization	80%
Proton beam polarization	70%



1st Detector Concept



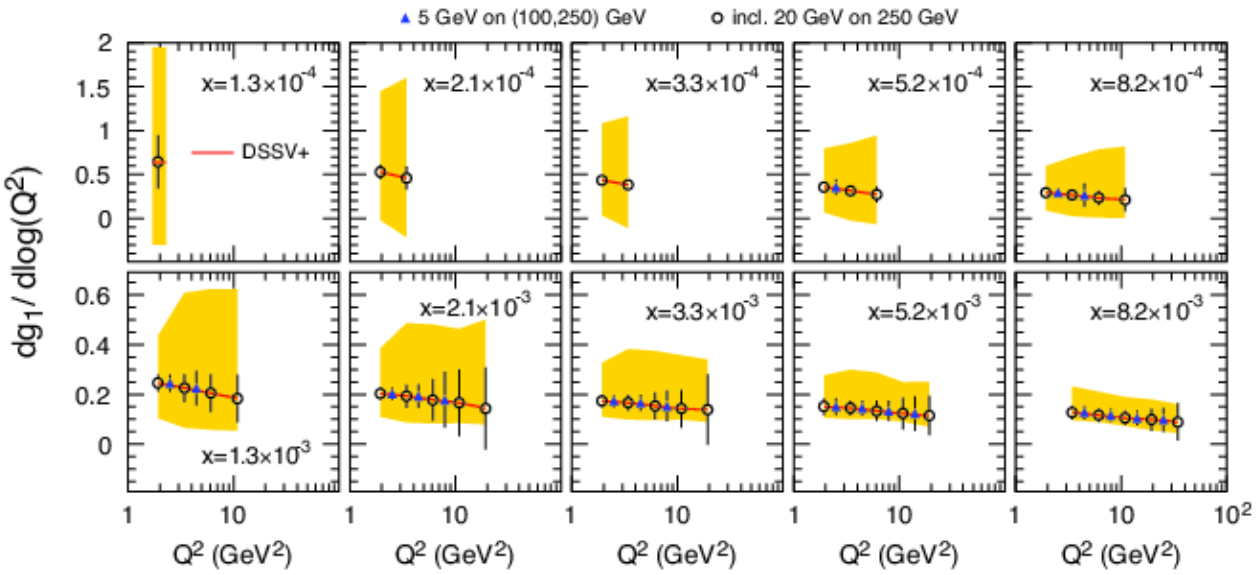


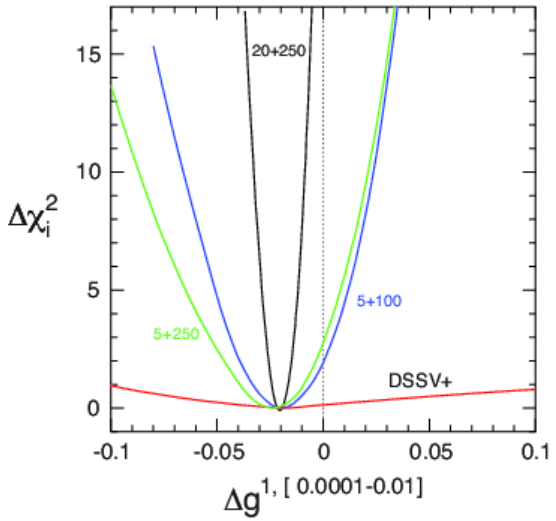
Electron Ion Collider: The Next QCD Frontier

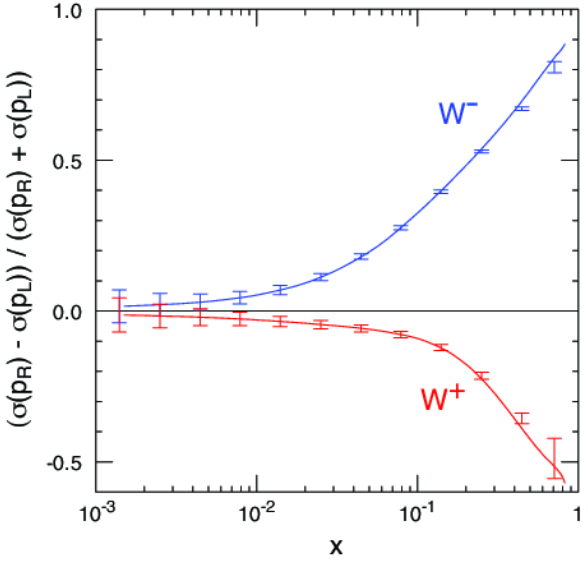
Understanding the glue that binds us all

arXiv:1212.1701
http://www.bnl.gov/npp/docs/EIC_White_Paper_Final.pdf

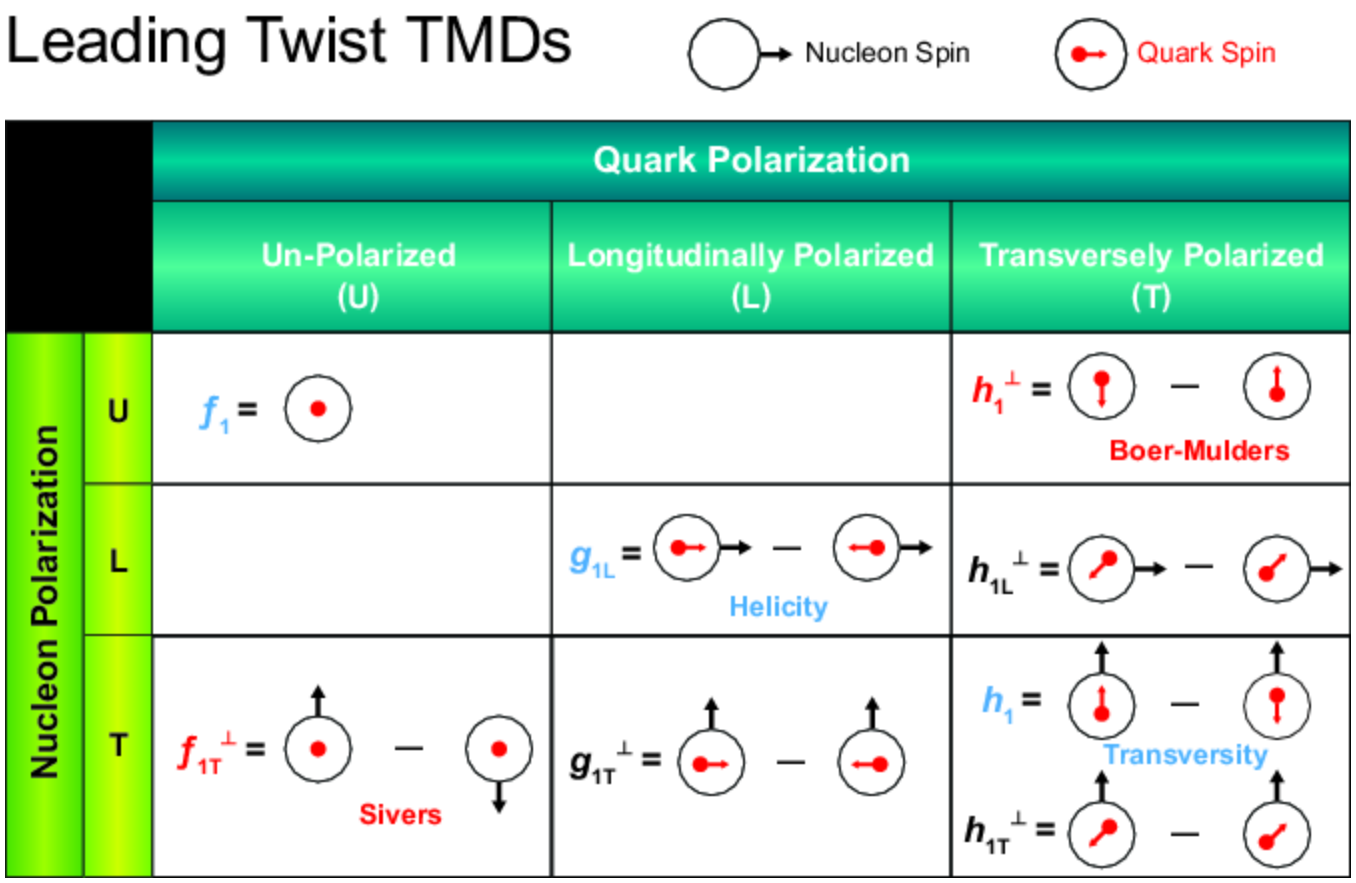
Longitudinal Spin Structure



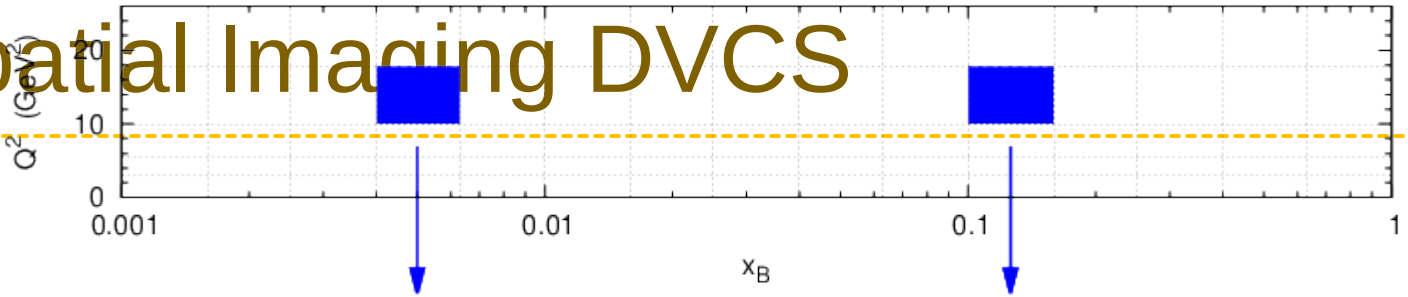




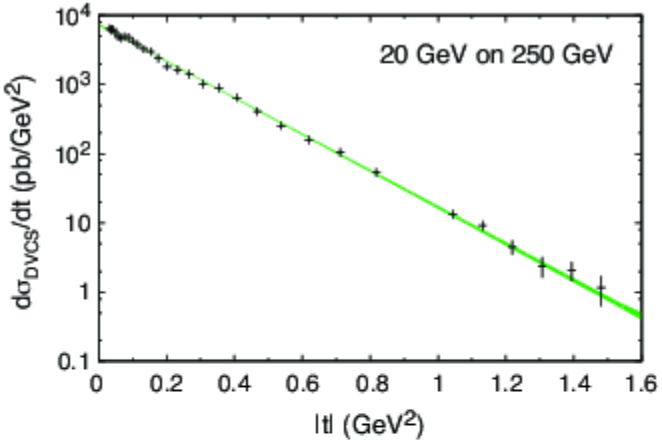
Transverse Momentum Dependence



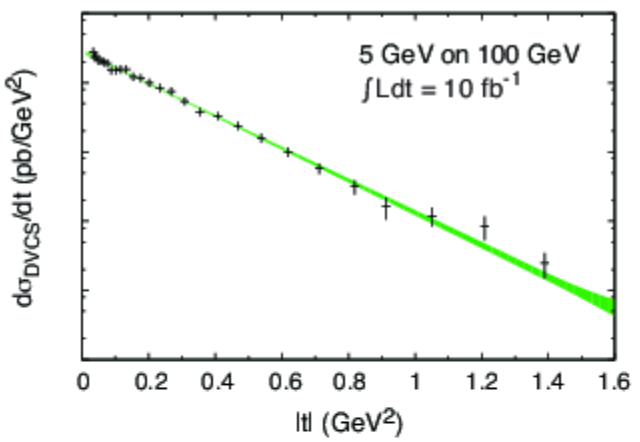
Spatial Imaging DVCS

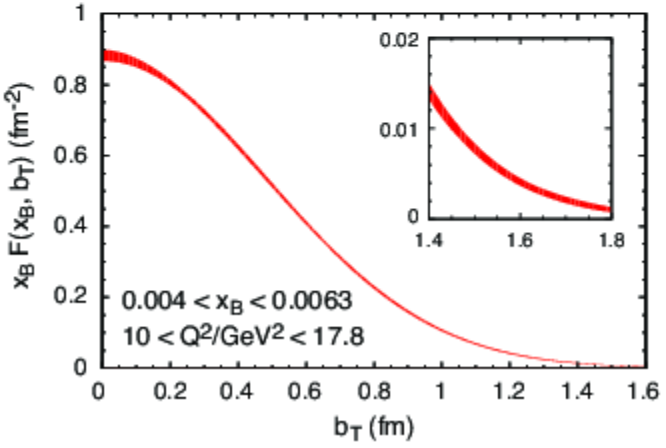


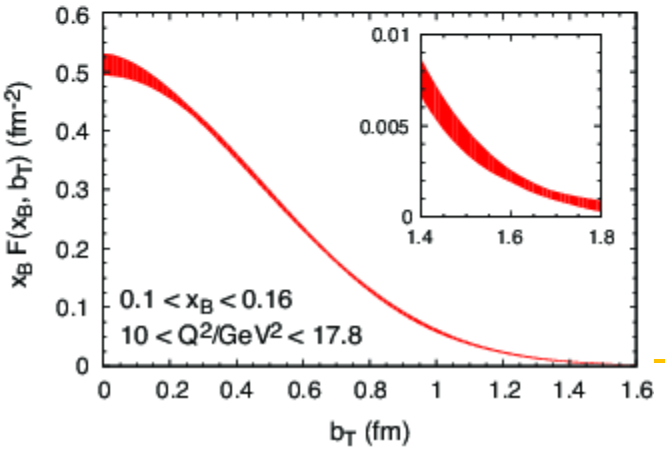
$\gamma^* + p \rightarrow \gamma + p$



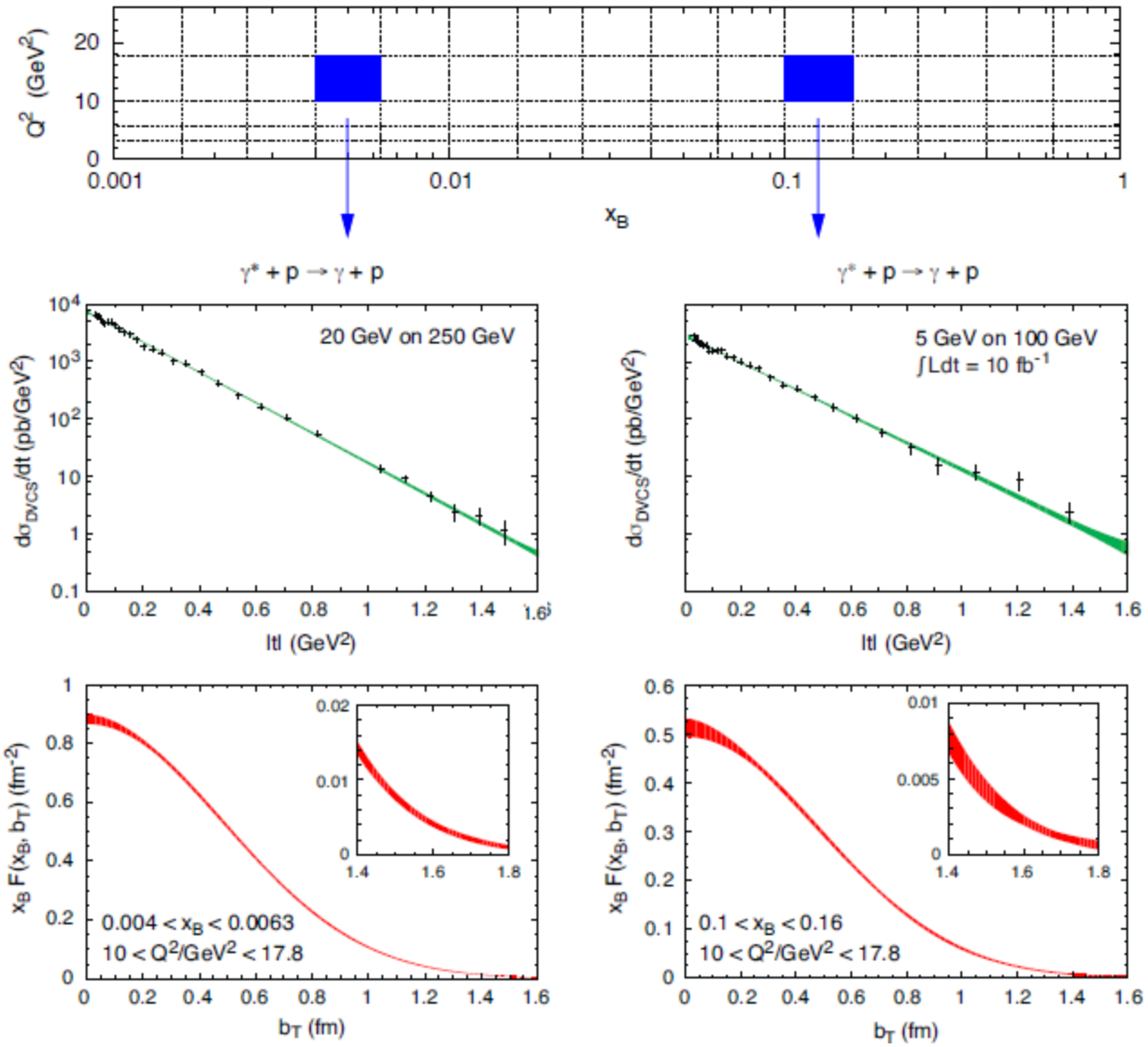
$\gamma^* + p \rightarrow \gamma + p$



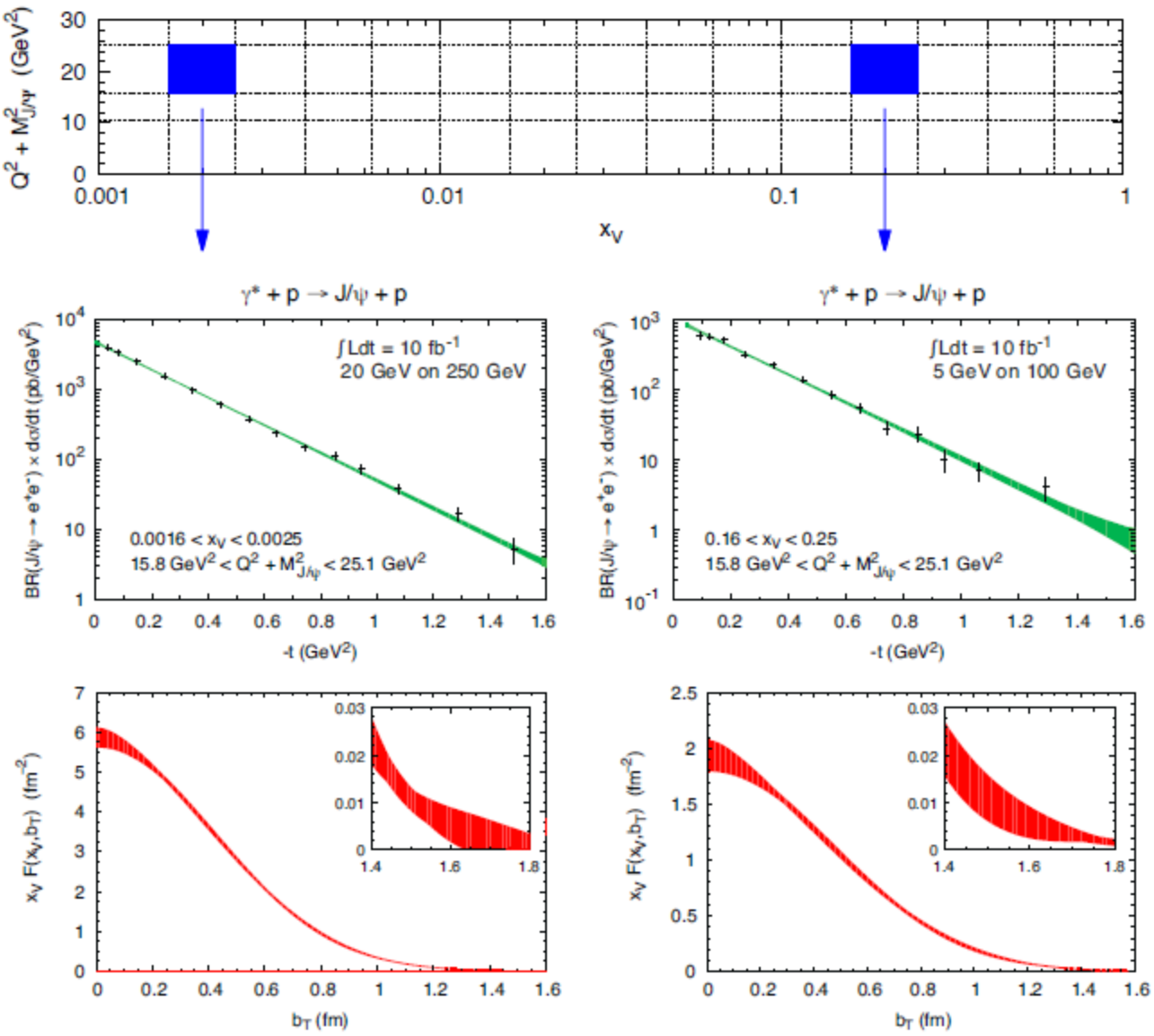




DVCS


Q^2 (GeV^2)
20
10
0
0.001
0.01
0.1
1
x_B
$\gamma^* + p \rightarrow \gamma + p$
$\gamma^* + p \rightarrow \gamma + p$
$d\sigma_{DVCS}/dt$ (pb/GeV^2)
20 GeV on 250 GeV
10^4
10^3
10^2
10
1
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
|t| (GeV^2)
$d\sigma_{DVCS}/dt$ (pb/GeV^2)
5 GeV on 100 GeV
$\int$Ldt = 10 fb^{-1}
|t| (GeV^2)
$x_B F(x_B, b_T)$ (fm^{-2})
0.02
0.01
0
1.4
1.6
1.8
$0.004 < x_B < 0.0063$
$10 < Q^2/\text{GeV}^2 < 17.8$
b_T (fm)
$x_B F(x_B, b_T)$ (fm^{-2})
0.01
0.005
0
$0.1 < x_B < 0.16$
$10 < Q^2/\text{GeV}^2 < 17.8$
b_T (fm)

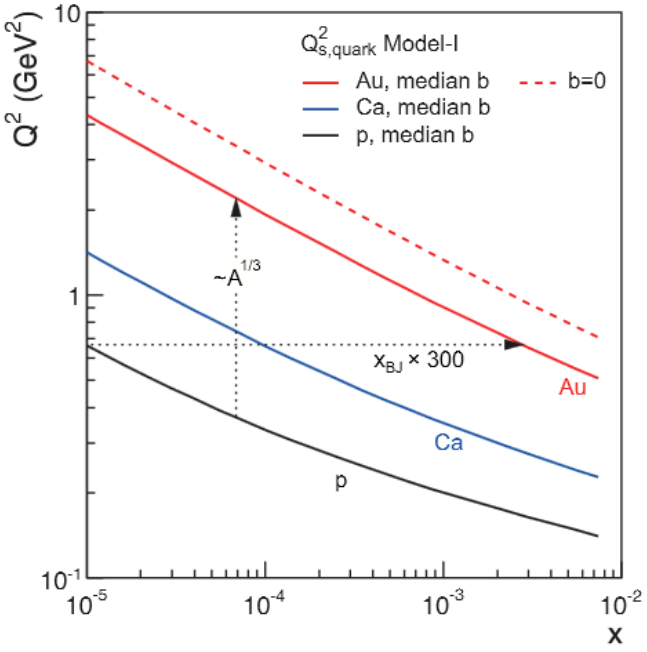
VM

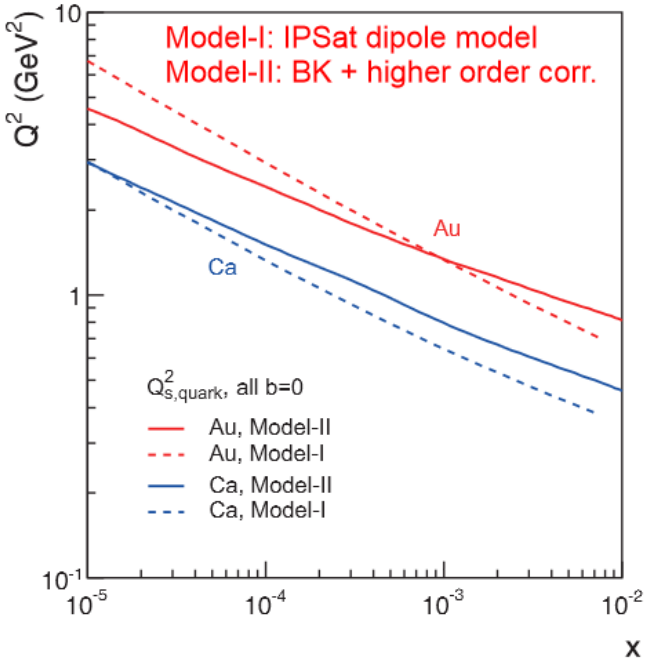

$Q^2 + M^2_{J/\psi}$ (GeV^2)
30
20
10
0
0.001
0.01
0.1
1
x_V
$\gamma^* + p \to J/\psi + p$
$\int Ldt = 10$ fb^{-1}
20 GeV on 250 GeV
$0.0016 < x_V < 0.0025$
15.8 GeV$^2 < Q^2 + M^2_{J/\psi} < 25.1$ GeV^2
BR($J/\psi \to e^+e^-$) $\times$ dσ/dt (pb/GeV^2)
-t (GeV^2)
$\gamma^* + p \to J/\psi + p$
$\int Ldt = 10$ fb^{-1}
5 GeV on 100 GeV
$0.16 < x_V < 0.25$
15.8 GeV$^2 < Q^2 + M^2_{J/\psi} < 25.1$ GeV^2
BR($J/\psi \to e^+e^-$) $\times$ dσ/dt (pb/GeV^2)
-t (GeV^2)
$x_V F(x_V, b_T)$ (fm^{-2})
b_T (fm)
$x_V F(x_V, b_T)$ (fm^{-2})
b_T (fm)

Saturation Scale Q_S

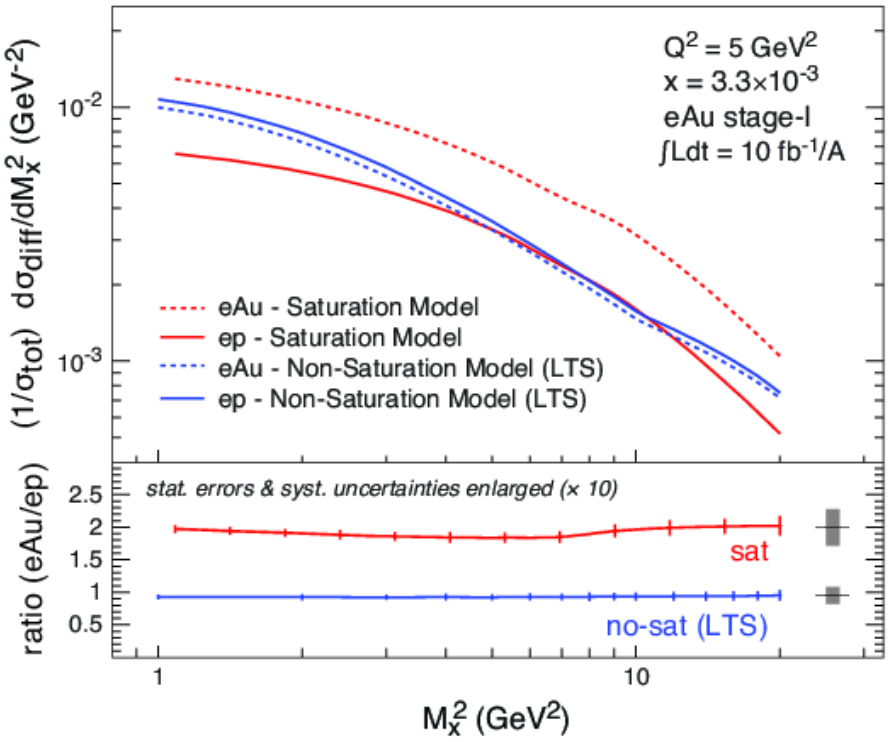
The ultra-relativistic boost amplifies the gluon densities in a nucleus $R \sim A^{1/3}$

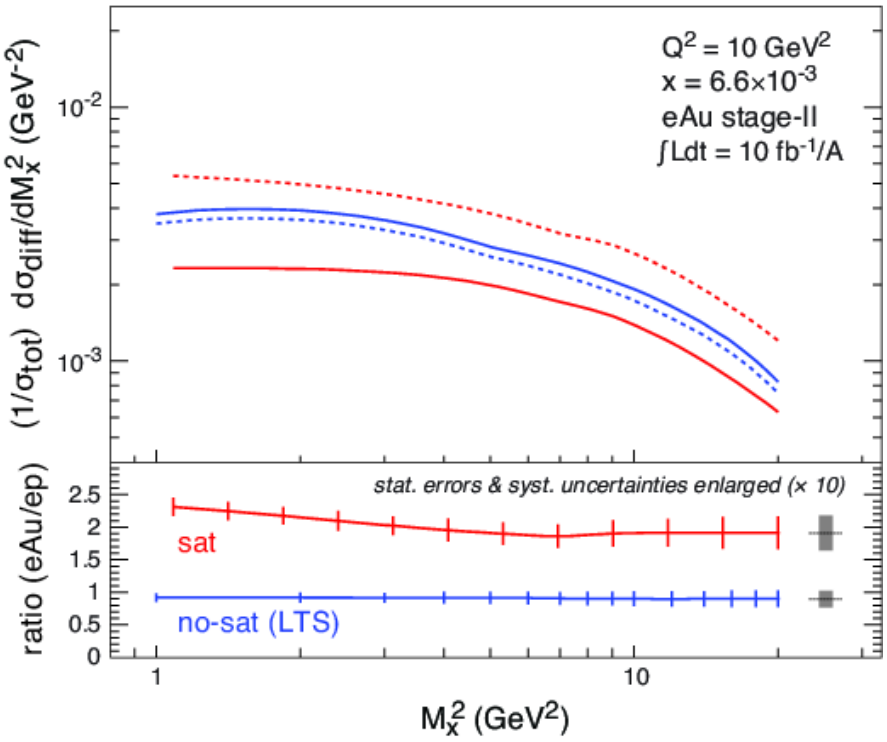
$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$





Diffractive Cross Section





DIS Kinematics

Scattered electron

$Q^2 > 1\ \mathrm{GeV}^2$

$0.01 < y < 0.95$

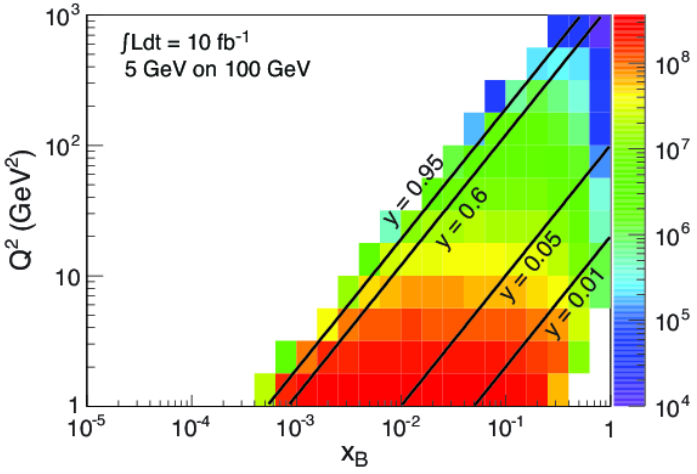
$0.1 < z$

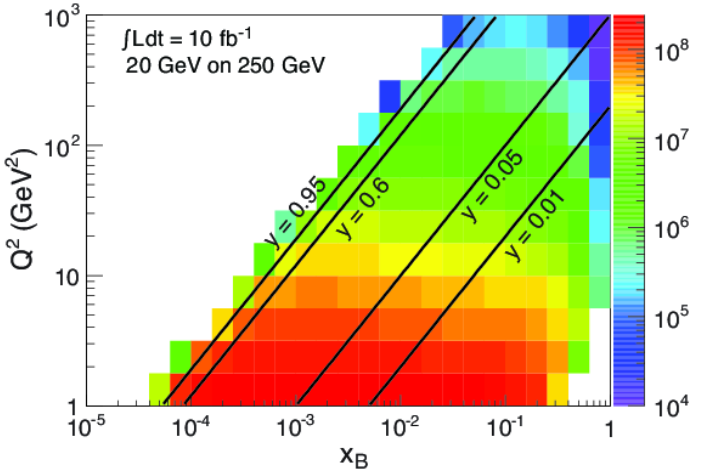
$-5 < \eta < 5$

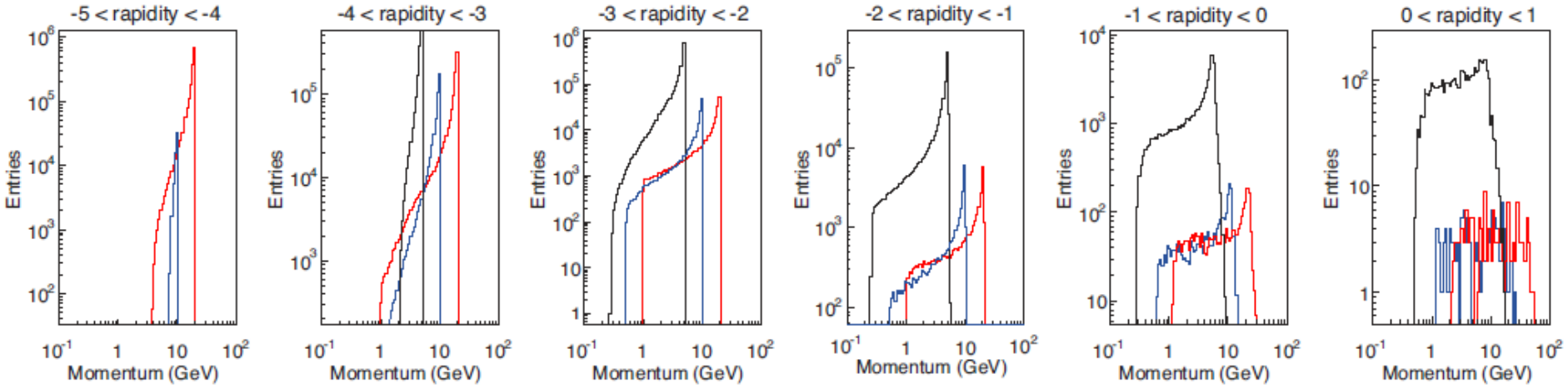
5 GeV x 50 GeV

10 GeV x 100 GeV

20 GeV x 250 GeV







SIDIS Kinematics

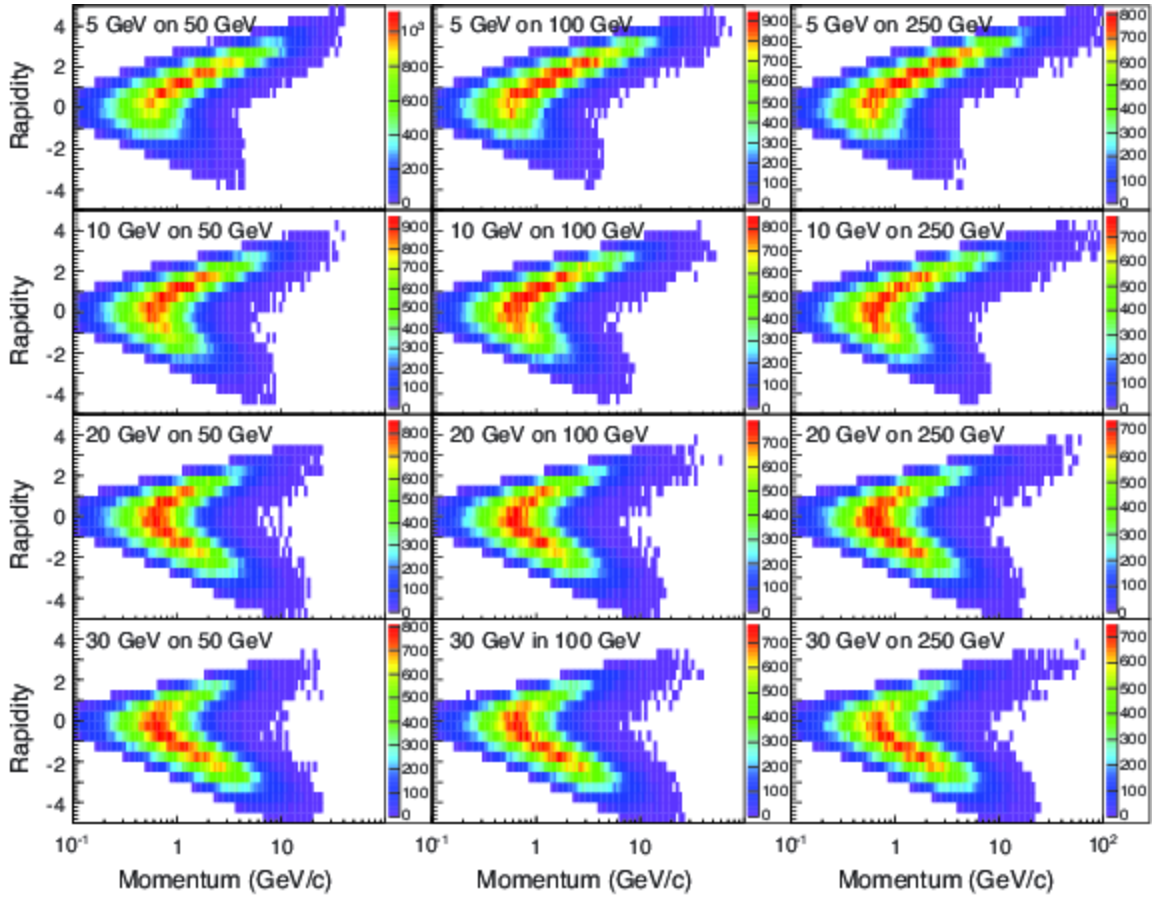
Non-exclusive pion

$$Q^2 > 1\ \mathrm{GeV}^2$$

$$0.01 < y < 0.95$$

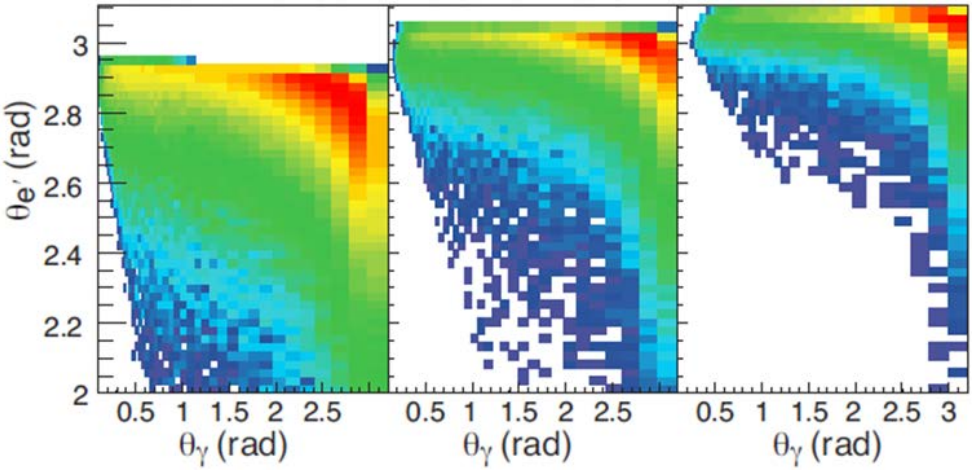
$$0.1 < z$$

$$-5 < \eta < 5$$

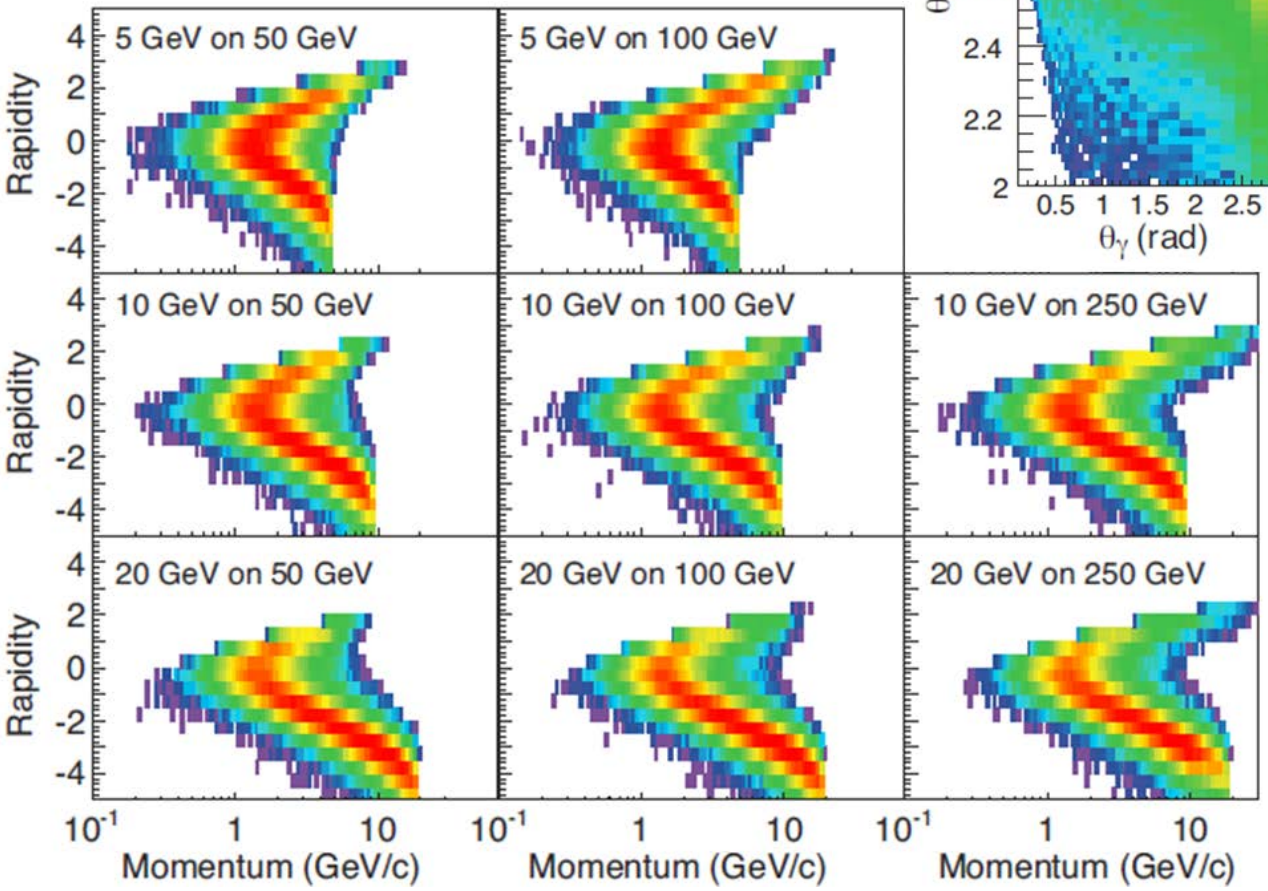


DVCS Kinematics

5 GeV x 100 GeV 10 GeV x 100 GeV 20 GeV x 100 GeV



Photon in lab. frame



Precision Measurement of $\sin^2 \theta_W^{eff}$